COMPUTER AIDED DESIGN OF MODULAR FIXTURES

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CERTIFICATE

It is certified that the work contained in the thesis entitled *"Computer-aided Design of Modular Fixtures"*, by *"Puneet Tandon"* has been carried out under our supervision and this work has not been submitted elsewhere for a degree.

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ABSTRACT

The motivation for this work is the automation of fixture design, which is currently performed manually, in order to achieve complete automation of machining planning and total integration of computer aided design and manufacturing. Though there have been many research efforts toward the automation of machining planning, fixture design, unfortunately remains one of the least studied areas and it remains a major missing link in automating machining planning.

Basic research issues involved in fixture design are the selection of locating and clamping positions for a given workpiece alongwith its setup position, in order to achieve accurate locating, total restraint of the workpiece, no interference between fixture, workpiece and the cutting tool, and "goodness" of the design and the selection of different elements, which, when assembled lead to a complete fixture. For this algorithmic and heuristic methods were developed to synthesize and analyze fixture configuration.

A system is developed which designs fixtures for machining a prismatic part. Input to the system is a solid model of the final workpiece alongwith relevant process plan. Output from the system is geometric design and selection of fixture elements to configure the fixture to machine the part. The system is implemented and tested with numerous examples of prismatic parts.

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CHAPTER 1

INTRODUCTION

1.1 AUTOMATION AND MACHINING PLANNING

Machining Planning is an important link between design and manufacturing. It is responsible for successful and efficient translation of design information into product.

Automated design and manufacturing with intensive use of computers resulting into computer-aided design (CAD) and computer aided manufacturing (CAM) respectively have been important developments of the last three decades. Recently, over last one decade automation of machining planning has emerged as a bridge between CAD and CAM.

Automating machining planning has been reported to offer several advantages including shorter lead time, higher quality of machined parts, lower part cost and more flexibility in machining planning [Chang and Wysk (1985)] [Olling and Deng (1992)] [Requicha and Vandenbrande (1988)] [Turner et al. (1991)].

The machining planning as the planning activity performed between product drawing and actual machining is complex and ill-defined. Manufacturing planning, process planning, process engineering, machine routing and machining planning are some of the titles given to the same activity.

Machining Planning is the systematic determination of the methods and means by which a product is to be manufactured economically [Chang and Wysk (1985)].

The *machining planning* involves several or all of the ollowing functions:

i) Blank Selection: Given the finished part geometry, a raw ıaterial form must be selected.

ii) Feature Recognition: The final part geometry is analyzed .o identity various features for machining.

(iii) Operation Selection: For each feature in the finished ɔart, a set of machining operations capable of producing it economically must be selected.

(iv) Operation Sequencing: The order of applying these operations must be determined. This sequencing is influenced by several factors such as accessibility, set up and tolerance.

(v) Machine and Cutting Tool Selection: For each machining operation or a group of machining operations to be performed, a machine and a cutting tool must be selected.

(vi) Set up Planning: A series of orientations of the workpiece, locating faces and features to be produced in each workpiece orientation must be determined.

(vii) Fixture Design/Selection: For each set up detailed fixture configuration must be designed, and/or a suitable set of fixtures from the available list should be selected.

(viii) Operation Parameter Selection: Operation parameters such as feed rate, spindle speed and depth of cut, must be selected. These can be selected from machining data handbooks.

(ix) NC Code Generation and Part Programming: NC codes to drive NC machines must be generated.

Though these tasks are listed roughly in the order they are ›erformed, the interactions among them are very intimate and these .asks are performed in an iterative way. For example, operation ;equencing will not be complete until a sequence of setups is ›lanned and a sequence of setups is not complete until the :easibility of fixturing in each setup is confirmed. Yet, the ıbove tasks are usually divided into two groups. The tasks from naterial selection to setup planning are grouped into <u>process</u> <u>ɔlanning</u> and the remaining tasks, operation parameter selection ınd NC code generation and part programming are grouped into <u>ɔperation</u> <u>planning</u>. Process planning and the operation planning ıre performed by process planners and operation planners and <u>routing</u> <u>sheet</u> and the <u>operation</u> <u>sheet</u> are the resulting outputs respectively. A process plan lists the operations in their sequential order that must be performed in order to produce the part, alongwith the machine and the tooling that will be required for each operation. An operation plan provides more detailed information such as cutters, feed rates, spindle speeds, depths of cuts and setup details. It is accompanied by NC codes.

1.2 COMPUTER AIDED PROCESS PLANNING

Process planning requires a significant amount of experience and time. Process planning of complicated parts takes days and even months. Thus it is tedious and error prone. Modern industry faces the scarcity of skilled labour to do the job. Inconsistency is another problem with manual process planning, as different

process planners perceive different processes from different angles. Process planning has become a gargantuan task due to a large variety of products and decreasing product life cycles in modern industry. It has further become complicated with the advent of *flexible manufacturing system* (FMS) environment.

Advent of computers in manufacturing made a considerable dent on process planning and this resulted in *Computer Aided Process Planning* (CAPP) systems. In CAPP, a computer does either several or all of the process planning functions. The development of NC machine tools in fifties replaced the task of generating manually cumbersome cutter path instructions by computer generated NC code. Database management systems for the storage and retrieval of process plane were developed in sixties. Computer aided systems for the selection of processes, machine tools, cutting tools, jigs and fixtures have been developed since late seventies. First generation CAPP systems required human intervention to process the design diagram of the object and to convert it into a computer readable form, code or specialized language. In early eighties it was realized that CAD systems provide a computer readable part description [Requicha and Vandenbrande (1980)]. Human intervention can be minimized to a great extent if this part description is used as input to CAPP systems. After reading the part description, obtained from CAD drawings, the manufacturing features present in the part are recognized. This is called *Feature Recognition* , which is not a trivial problem. Most of the ongoing research in CAPP is directed towards a generic feature recognition system, which is very essential to the complete

integration of CAD and CAM.

1.3 APPROACHES TO CAPP

These are two basic approaches to CAPP - *variant* and *generative*. In variant approach an existing process plan of a similar component is retrieved and is edited to create its 'variant' to suit the specific requirement of a component being planned. In generative approach, a new process plan is generated for each component without referring to existing plans.

VARIANT PROCESS PLANNING

It is based on the concept that similar parts have similar process plans. There are two stages in developing a variant process planning system - preparatory and production.

During the preparatory stage, a coding scheme, encompassing various characteristics and attributes like geometric shapes and process similarities, is established. The existing components are coded, classified and grouped into part families, depending on the similarities in codes. Families can be described by a set of family matrices. Each family is a binary matrix with a column for each digit in code and a row for each value a code digit can take. A non-zero element in the matrix indicates that the particular digit can have the value of that row, e.g. element (3,2) equals one implies that a code X3XXX can be a member of the family. A standard plan is a process plan to manufacture the entire family. This preparatory stage is a time consuming process.

During the production stage, the system is ready to create process plans for new parts. A new part is coded, the code is used to retrieve the standard plan of the family to which it belongs. Then the standard plan is edited.

Variant process planning is very easy to understand, learn and use. Process planner has full control over the final plan. It is especially useful for manufacturing industries which produce similar components repetitively. The system cannot be used for radically different parts. Since human intervention is still required, complete automation is not possible with variant process planning.

GENERATIVE PROCESS PLANNING

In generative process planning, process information is synthesized to create a process plan of a new part automatically. A generative process planning has three components - Part description, Decision logic and algorithms, and Manufacturing data bases.

Part description is the front end of a generative CAPP system, through which, the geometry, dimensioning and surface quality requirements for a machined part are defined. The first generation of generative CAPP systems used coding based on design and/or manufacturing attributes. OPITZ, DCLASS, and MICLASS [Chang and Wysk (1985)] are such coding systems. APPAS and GENPLAN use coding systems in description modules. But coding requires considerable human intervention and exact information is lost when a part is coded by finite digits of code. This limitation led to the development of special description

languages.

AUTAP system uses a descriptive language in which a part is described using geometric feature elements such as cylinders, chamfer, radius and technological elements like tolerance. In CIMS part description system, a part shape is described using volumetric elements obtained by revolving or translating of generating surfaces. Each generating surface is a concatenation of profile elements given by directed line segments. Technological information can be supplied to each profile element.

Decision logic and algorithms module imitates the decision making function of a process planner. These functions include all or several of process planning functions. The decision logic is represented using decision trees, decision tables and Artificial Intelligence techniques. Algorithms are used to perform computations and guide the system during decision making process.

Manufacturing databases module stores the manufacturing knowledge. The knowledge representation methods are related directly to the decision logic because static data is the representation and dynamic use of the data becomes the decision logic. Several databases are required to provide a process planning system with the information required for making decisions.

1.4 RESEARCH TRENDS IN PROCESS PLANNING

Earlier research in process planning was concentrated on the variant approach. In 70's group technology (GT) based variant

process planning systems were developed. Those systems could neither made decisions nor help in making decisions, since there was no intelligence involved in them. But trends in manufacturing since 80's have shown a demand for a large variety of parts. As the variant process planning can only work in a machine shop involving the production of similar parts, it could not meet the requirements and focus of research shifted towards the generative process planning.

Research in the first generation of generative process planning i.e., in early 80's, was directed at the development of better methods for representation of decision logic and manufacturing databases. A generative process planning system contains tremendous amount of knowledge rules in decision making and facts about the machine shop. These rules need updating with the rapid advances in manufacturing technologies. Traditional systems do not allow the updating of facts and rules as they are coded line by line in the program statements. This rigidity is overcome by the application of Artificial Intelligence(AI) and expert systems. An expert system stores the knowledge in a special manner so that it is possible to add, delete, and modify rules and facts in the knowledge base without rewriting the program.

The declarative facts in an expert system are the knowledge about machine tools, cutting tools, jigs and fixtures, and machining operations. Procedural rules store the decision logic involved in the selection of operations, machine tools, cutting tools, jigs and fixtures, operation sequences and machining

parameters. They are generally in the form of condition/action pair.

Machine learning, generation of multiple process plans, reasoning explanation and process planning under uncertainty are the future research topics in AI-based CAPP systems. A system should be able to accumulate the knowledge if user is more knowledgeable than the system. However, the incorrect and inconsistent information should be checked.

Earlier generative process planning systems used either codes or special languages to describe a part. Part description in these method required human efforts to process the design drawing. Since mid - 80's, CAD models are being used to supply part description to CAPP systems.

Integrating and interfacing of process planning with other manufacturing functions, like scheduling and shop floor control, is another major research issue. Since route sheets generated by process planning forms input to scheduling, the integration of process planning and scheduling is very essential. Scheduling generates an optimal schedule based on the optimal route sheets generated by process planning. Since this hierarchical optimization may not give globally optimized schedules, the integration seems to be a desirable one.

1.5 IMPORTANCE OF AUTOMATING MACHINING PLANNING

Though there is not any data on how important it is to automate machining planning, there are some facts and speculations

that make us think it is important to automate machining planning.

Presently, parts which qualify for mass production account for not more than 25% of the total value of metal working production in all industrialized metal working nations. One half of the remaining 75% is produced in job lots of less than 50 workpieces. The number of these parts are increasing each year and their complexity and requirement for accuracy are also increasing. Social and technological trends such as demands for customized products, shorter product lives, higher reliability of products, along with superior process tolerances and a wider variety of materials, are some of the driving forces behind the need of smaller batch sizes [Zeid (1991)]. Accordingly industry is leaning toward flexible manufacturing systems (FMS) to meet the demand of smaller batch sizes and the ever increasing demand for productivity improvement.

As FMS advances, less people are seen on the shopfloor; but in the office next to shop floor, many people are seen working on machining planning in a labour intensive way. This manual machining planning is inflexible to disturbances such as engineering changes and emergency orders and lessens the flexibility of FMS. Manual machining planning has another problem. Since process planning is based on the previous experience of the planner, personal preference, extent of shop knowledge, interpretation of design requirements and other judgment factors, process plans are often inaccurate, inconsistent and faulty.

Automating this labour intensive machining planning offers benefits of more than just saving labour cost of manual machining planning. More importantly, it offers the possibility of shorter lead time, higher quality of machined parts, lower part cost, scheduling flexibility and flexibility to disturbances.

1.6 OBJECTIVE AND SCOPE OF THE PRESENT WORK AND ORGANIZATION OF THE THESIS

There have been many research efforts aimed at automating machining planning but, unfortunately, fixture design is one of the least studied areas and it is a major missing link in automating machining planning. It is a considered to be a difficult area to automate because it involves a lot of non algorithmic and heuristic reasoning on the geometry of the finished part, intermediate work piece, fixture components and tool path movement. Besides, the area of computational geometry is not so advance, so as to deal with all types of problems [Preparata and Shamos (1985)].

Integration of process planning with automated fixture design is one of the major areas, requiring immediate and apt attention of the researchers in this field. At present, almost most of the computer aided process planning (CAPP) systems, does not have the facility of automatic fixture designing, as this part of CAPP is quite complicated and carries a lot of bottlenecks needed to be overcome. Hence, automated fixture designing is another major research issue of process planning.

PROBLEM STATEMENT

The primary objective of this work is to find for a given dimensioned solid model of a prismatic part, the fixture configuration for machining which satisfies the following requirements:

1. Accurate locating of the workpiece
2. Total restraint of the workpiece during machining
3. Limited deformation of the workpiece
4. No interference between the fixture components and cutting tool.
5. "Goodness"

Here a prismatic part is defined as a part which can be located and clamped on its planar faces horizontally and/or vertically in relation to the base plate of machine table.

The present work is able to achieve accurate locating of the workpiece, total restraint of the workpiece during machining, no interference between the fixture components and cutting tool and some aspects of merit of design like smaller number of fixture components and ease of loading of a workpiece. This work doesnot attempts on workpiece deformation due to complicated Finite Element Analysis (FEA) involved.

Chapter 2 after discussing the usefulness of fixture for machining, provides a technical glance on principles of fixture design and the fixture design procedure. It further provides a brief information on the designing of locating, positioning and clamping devices.

Chapter 3 lists out most of the work done in the area of automated fixture design till date. It briefly discusses the nature of work done, their achievements and limitations.

Chapter 4 besides enlisting the essential requirements of a fixture, provides an insight into the automated fixture designing systems, and modular fixtures. Finally, this chapter throws light on 'fixture design system structure' and various modules of the system, developed by the present work.

Chapter 5 involves the consideration of machining forces in designing different elements of the fixture. This task is accomplished with the help of compliance analysis.

Chapter 6 presents system design, its implementation and some illustrations.

Chapter 7 gives the conclusions and limitations of the present work and suggestions for the future work.

CHAPTER 2

FIXTURE DESIGN: A BRIEF TECHNOLOGICAL PERSPECTIVE

Jigs and fixtures are not, and often can not be, designed on drawing board. While the details of a design are developed as the drafting proceeds, its main feature should have been conceived in the designer's mind before the start of sketches and working drawings [ASTME (1962)].

A successful fixture design is the result of the designer's ability to analyze all information and conditions pertinent to a given manufacturing operation and to incorporate design features that offset or eliminate all possible problems associated with the operation.

If a fixture fails, it is either because of faulty analysis, or because the fixture designed didnot overcome the problems and difficulties that were clearly shown at the analysis stage. Irregular workpieces, such as castings and forgings or workpieces having variations in size, properties etc., can be main cause of improper functioning of a fixture. The characteristics and properties of the workpiece are known at the beginning of fixture planning; therefore all possible non uniformities and variations in a work material will have to be considered in its analysis as a basis for subsequent decisions in planning the fixture as a whole.

There is no infallible procedure that can be applied to any design problem and will automatically ensure the conception of a perfect or nearly perfect design of a fixture. There is no

formula in which the fixture designer can insert values and evolve perfection in the design of a fixture.

The use of fixtures is extending and developing very fast [Houghton (1956)]. To mention few points in their favour, the use of fixtures provides the following:

1. Eliminates the costly and laborious marking out and setting up of each workpiece before machining.
2. Increases the machining accuracy and ensures interchangeability.
3. Increases productively
4. Saves operation labour.
5. Utilization of lower skilled labour.
6. Decreases expenditure on quality control.
7. Increases industrial safety.
8. Increases the versatility of machining performed.
9. Either fully or partly automates the machine tool

2.1 PRINCIPLES OF FIXTURE DESIGN

A fixture must position or locate a workpiece in a definite relation to the cutting tool and must withstand holding and cutting forces while maintaining the precise location. A fixture is made up of several elements, each performing a certain function. The locating elements position the workpiece; the structure withstand the forces; brackets attach the workholder to the machine, and clamps, screws and jaws apply holding forces. All functions must be performed with the required firmness of

holding, accuracy of positioning, and with a high degree of safety for the operator and the equipment. With any fixture design the aim should be simplicity [ASTME (1987)]. Some of the principles are discussed below:

1. Reduction of idle time by improving methods of location and clamping.
2. Fixtures must be rigid enough to withstand cutting and clamping forces.
3. There should be plenty of clearance between the fixture and the component to take care of variations in dimensions in mass manufacture.
4. A good swarf clearance should also be provided.
5. Locating and supporting surfaces should where ever possible be removable.
6. Locating points should be clearly defined.
7. For easy removal of worn out locating or supporting pins, these should be fitted in through holes and not blind holes.
8. Fixture should be designed to receive the workpiece in only one position.
9. The process of loading and unloading the workpiece should be as easy as possible.
10. Clamping should always be done on planes directly opposite to the planes which are used for location.
11. Safety requirements must always dictate fixture design or selection.

2.2 DESIGN PROCEDURE

A systematic and orderly procedure for fixture design consists of five major phases or steps [ASTME (1962)] (Fig 2.1). These phases need not be necessarily followed in the same order in all the cases.

First Phase: The examination of all information pertinent to the product/workpiece as given by engineering and/or manufacturing drawings and the operation or process sheets. (Table 2.1 and 2.2.)

Second Phase: Conceptual design based on the information analysis in phase I. The scope of phase II are outlined in Table 2.3.

Third Phase: The examination and evaluation of criteria associated with the operation (process) (Table 2.2) further modifies some fixture design concepts. Those which are modified are wholly dependent upon operation criteria unique to (1) the type of operation (2) the sequence of operations; and (3) specific machine characteristic as tested in Table 2.4.

Fourth Phase: This phase consists of the examination of all accumulated design concepts and their possible change because of operator considerations, which consist of the elements of time, fatigue and safety.

Fifth Phase: The final phase is the evaluation of the tentative design(s) for lowest fixturing cost per part or any such criteria.

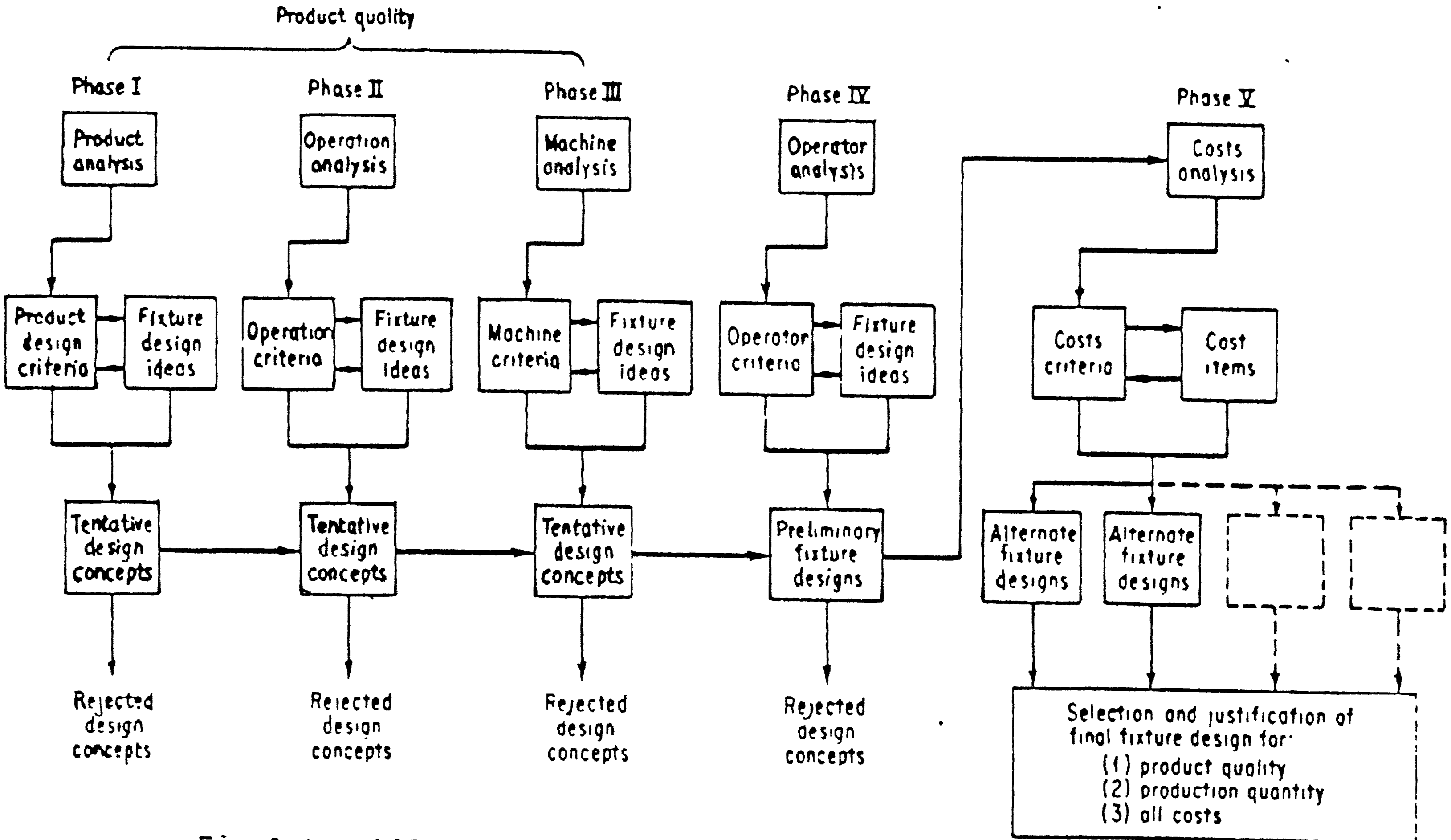


Fig 2.1 Different Phases in Fixture Design [ASTME (1962)]

Table 2.1 Product Analysis Criteria for Fixture Predesign (Phase 1) [ASTME (1962)]

1. Type *a* Casting *b* Stamping *c* Mill shape *d* Other 2 Kind *a* Ferrous *b* Nonferrous *c* Nonmetallic 3 Properties *a* Strength *b* Hardness *c* Ductility *d* Machinability *e* Weight (1) Amount (2) Distribution (center of gravity) *f* Rigidity *g* Resistance (electrical) *h* Conductivity (thermal)	4 Geometry (general shape and size) *a* Cylindrical *b* Flat (1) Circular (2) Rectangular *c* Spherical *d* Trapezoidal *e* Pyramidal *f* Conical *g* Combined shapes 5 Specifications (holes, bosses, slots, other surfaces or points) *a* Numbers *b* Sizes *c*. Location *d* Linear relations (tolerances) *e* Angular relations (tolerances) *f*. Finish *g*. Other

Table 2.2 Operation Classification and Criteria for Fixture-Predesign Analysis (Phase II) [ASTME (1962)]

I. Type *A*. Machining 1. Drill 2. Ream 3. Bore 4. Grind 5. Mill 6. Hone 7. Broach 8. Brush 9. Polish 10. Tap 11. Thread 12 Plane 13 Shape 14. Slot 15. Electromachine 16. Manual 17. Other *B*. Assembling 1. Rivet 2. Stitch 3 Staple 4. Braze 5. Weld 6. Solder 7. Bond 8 Fasten *a*. Bolt *b*. Screw *c* Special types	9. Press-fit 10. Stake 11. Tab-bend 12. O ring, seal, and gasket-material insertion 13. Other *C*. Inspection (qualification, gaging) 1. Angular relations 2. Linear relations 3. Concentricity 4. Surface conditions 5. Others, such as leakage testing *D*. Miscellaneous fixtures for 1. Heat-treating 2. Plating 3. Painting (masks) 4. Foundries 5. Cooling of plastic parts II Number and order *A*. Single *B*. Multiple 1. Sequential 2. Simultaneous

Table 2.3 Fixture-design Considerations [ASTME (1962)]

1 Locating considerations
- *a* Radial
- *b* Concentric
- *c* From surfaces
- *d* From points
- *e* Other

2 Positioning considerations (relation to tool and orientation in the fixture)
- *a* Indexing (linear and circular)
- *b* Rotating
- *c* Sliding
- *d* Tilting

3 Clamping considerations
- *a* Rapidity
- *b* Amount of clamping forces
- *c* Direction of clamping forces
- *d* Actuation (manual power)

4 Supporting considerations
- *a* Relation to tool forces
- *b* Relation to clamping pressure
- *c* Relation to thin walls, sections of workpiece

5 Loading considerations (including manual lifting and sliding, hoisting, unloading chutes, magazines)
- *a* Rapidity
- *b* Ease
- *c* Safety

6 Coolant considerations
- *a* Direction

7 Chip considerations
- *a* Accumulation
- *b* Disposal

Table 2.4 Machine and Equipment Classification and Criteria Characteristics for fixture-predesign Analysis (Phase II [ASTME (1962)]

Class I Material removal

1. Milling type (vertical, etc.)
2. Drilling type (sensitive, etc)
3. Broaching type (pull-down, etc)
4. Boring type (horizontal, etc.)
5. Grinding type (surface, etc.)
6. Turning type (automatic lathe, etc)
7. Reciprocating type (planer, etc)
8. Honing
9. Electrical metal-removal type
10. Polish

Class II. Nonmachining

A Assembling
1. Welding type (resistance, etc.)
2. Riveting type (pedestal, etc)
3. Stapling, stitching
4. Soldering, brazing
   - *a* Electrical induction
   - *b.* Furnace
5. Other

B Inspection
1. Optical (comparator, etc)
   - *a* Stage area
2. Fixture indicating elements
   - *a* Mechanical (geared indicator, etc)
   - *b.* Air, hydraulic (indicators, gages)
   - *c.* Electric, electronic (pick-ups, meters)

C Miscellaneous equipment
1. Painting
2. Heat-treating
3. Plating
4. Foundry operations
5. Peening
6. Other

2.3 DESIGN OF LOCATING AND POSITIONING DEVICES

Workpiece locating will relate to the considerations involved in achievement of a desired dimensional and positional relationship between the workpiece and the workpiece-holding device [ASTME (1962)]. The proper solution of the workpiece locating problem required certain points (or surfaces) of contact between the workpiece and the workpiece holding device and may also require a definition of direction and degree of holding force.

For the purpose of workpiece - locating analysis, the four basic kinds of workpiece surfaces (which in various combinations make up the total configuration of any workpiece) are as follows:

1. Flat surface
2. Inside diameter or concave face
3. Outside diameter or convex face
4. An irregular surface, which is none of the above three type of surfaces.

Any one of the previously described four elemental surfaces can further be classified as (1) rough or (2) finished. The term "rough" is intended to designate a workpiece surface common to raw material such as castings, weldments, forgings etc. They have inherent dimensions variance. The term "finished" is intended to mean a smooth machined surface. The tooling most practical to locate the rough surfaces may have to be different from tooling to locate the finished surfaces.

2.3.1 LOCATING NOMENCLATURE

(i) **Plane Locating:** Locating flat workpiece surfaces.

(ii) **Concentric Locating:** Locating to an outside or inside diameter.

(iii) **Radial Locating:** After concentric locating, a supplementary requirement of locating is called radial locating e.g. as in wheel of chance.

The logical analysis of a workpiece - locating problem will be resolved into some combination or multiple of the above three different locating requirements. Before consideration of workpiece locating, the workpiece must first be analyzed to very clearly identify the essential workpiece - locating surfaces. Workpiece - locating surfaces are those surfaces which are to be the basis of alignment for workpiece locating. Fig. 2.2 and Fig. 2.3 illustrate the case for plane locating.

2.3.2 METHODS OF LOCATION

To insure successful operation of a fixture, the workpiece must be accurately located to establish a definite relationship between the cutting tool and some points or, surfaces of the workpiece [ASTME (1987)]. This relationship is established by locators, by which the workpiece can be positioned and restricted to prevent its movement from its predetermined location. The locating device should be so designed that each successive workpiece, when loaded and clamped will occupy the same position in the fixture.

A workpiece in space, free to move in any direction, is designed around three mutually perpendicular planes and may be said to have twelve degrees of freedom. It may move in either of two opposed directions along three mutually perpendicular axes, and may rotate in either of two opposed directions around each axis, clockwise and counterclockwise. Each direction of movement is considered one degree of freedom. The twelve degrees of freedom as applied to a rectangular prism are shown in Fig. 2.4. To accurately locate a workpiece, it must be confined to restrict it against movement in any of the twelve degrees of freedom except those called for by the operation.

A workpiece may be positively located by means of six pins, so positioned that collectively they restrict the workpiece in nine of its degrees of freedom. This is known as 3-2-1 method of location. Fig. 2.5 shows the prism resting on three pins A,B, and C. The faces of the three pins supporting the prism form a plane parallel to the plane that contains the X and Y axes. The prism cannot rotate about X and Y axes and it cannot move downward in the direction of freedom 5 i.e. negative Z direction. Therefore, freedoms 1,2,3,4 and 5 have been restricted.

In Fig 2.6, two additional pins D and E whose faces are in plane parallel to the plane containing the X and Z axes prevent rotation of the prism about the Z axis. It is not free to move to the left in the direction of freedom 8 i.e. negative Y. Therefore, freedoms 6,7, and 8 have been restricted and the prism cannot rotate.

Finally, with the addition of pin F as shown in Fig 2.7,

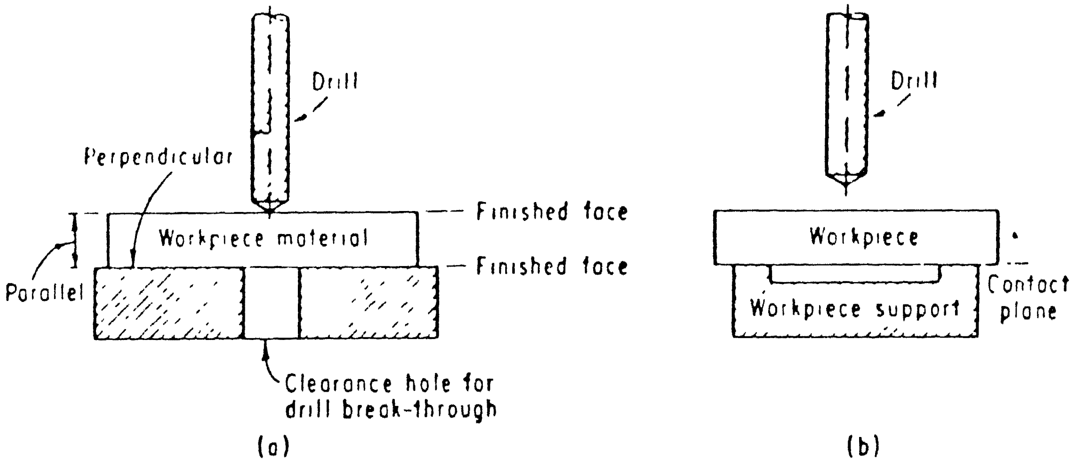


Fig 2.2 Plane Location

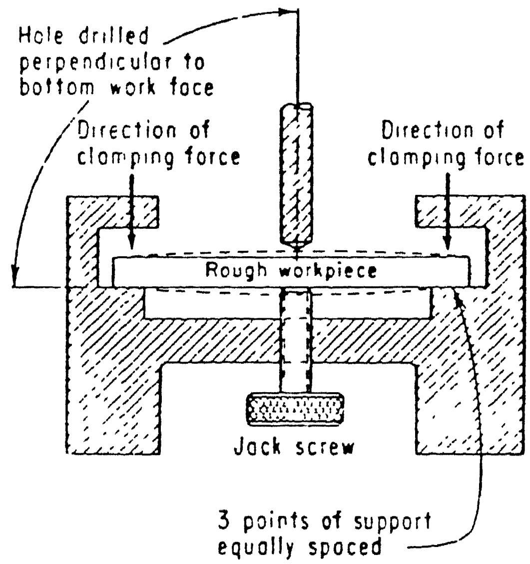


Fig 2.3 Plane Location to the rough Surface of a workpiece

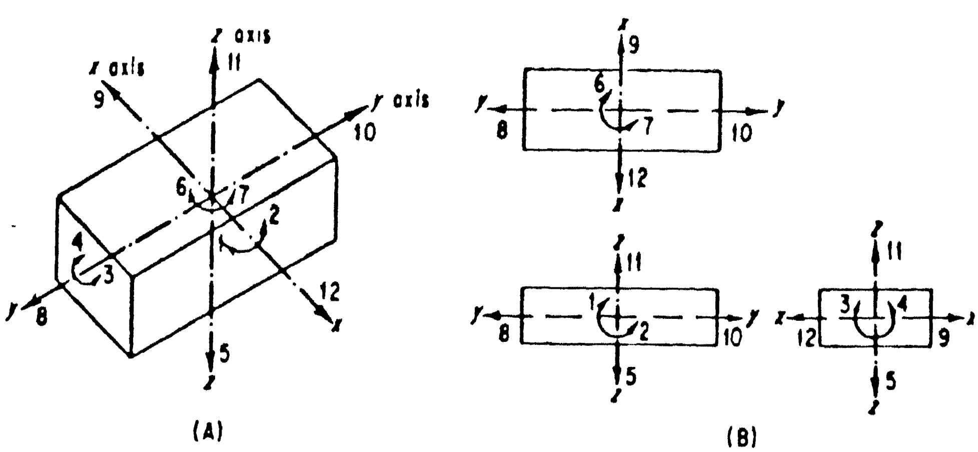


Fig 2.4 Twelve degrees of freedom

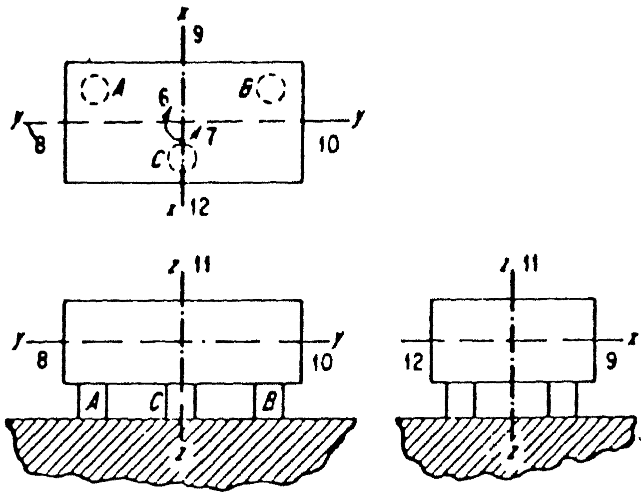


Fig 2.5 Three pins arrest five degrees of freedom

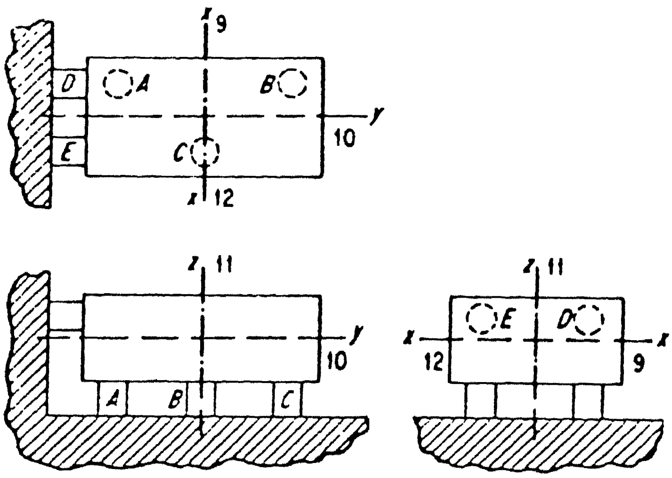


Fig 2.6 Five pins arrest eight degrees of freedom

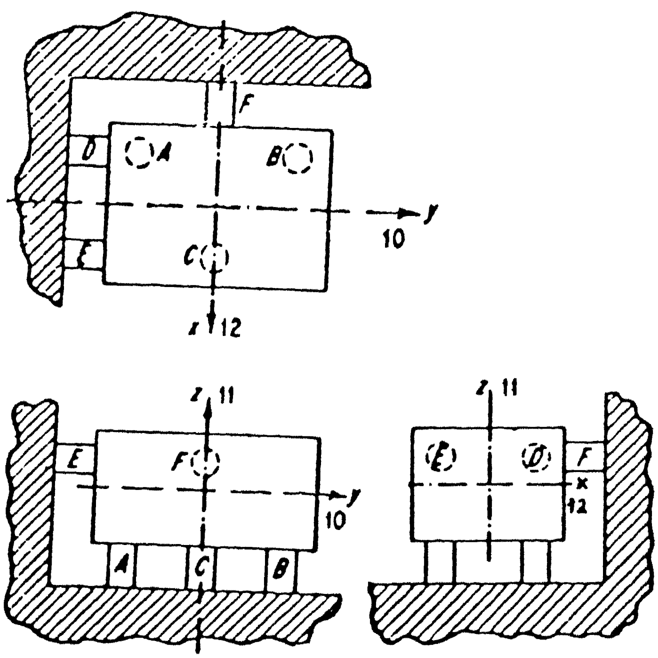


Fig 2.7 Six pins arrest nine degrees of freedom

freedom 9 is restricted. Thus by means of six locating points, three in a base plane, two in a vertical plane, and one in a plane perpendicular to the first two, nine degrees of freedom have been restricted.

Three degrees of freedom, 10,11,and 12, still remain unrestricted. The addition of three more pins, one for each remaining freedom, would completely restrict movement of the prism. The pins would then entirely enclose the workpiece. This is not practical since it would prevent loading of the workpiece into the workholding device. The remaining three freedoms may be restricted by means of clamping devices.

2.3.3 PRINCIPLES OF LOCATION

Various principles are:

1. The principle of *minimum locating points*. Points more than necessary should not be used to secure location in any one plane unless they serve a useful purpose.
2. The principle of *extreme positions*. Locating points should be chosen as far apart as possible on any workpiece surface so that for a given displacement of any locating point, the resulting deviation decreases.
3. The principle of *mutually perpendicular planes*. The most satisfactory locating points are those in mutually perpendicular planes. Others arrangements are possible but not desirable, two disadvantages result from locating from other than perpendicular surfaces:

(a) the consequent wedging action tends to lift the workpiece.

(b) the displacement of a locating point or a particle (chip or dirt) adhering to it introduces a correspondingly larger error (Fig. 2.8).

4. All locators should contact the workpiece on a machined surface or designated locating surface.
5. The reference surfaces, when not specifically indicated, should be those which are used to dimension the workpiece.
6. Locators should be positioned to avoid chips and foreign matters. When this is not possible, the locators should be relieved to prevent interference, when the workpiece is loaded or unloaded.
7. Locational tolerance should be as liberal as possible. Generally 20 to 30 percent is provided but upto 50 percent is O.K., otherwise cost will increase.
8. Work supports should be beneath the area at which the workpiece is to be clamped otherwise distortion or bending may take place.
9. The locating areas should be as small as possible.
10. All locating points which require replacement due to wear and tear should be easily replaceable or repairable.

2.3.4 LOCATING DEVICES

1. **Locating from a flat surface**

   The following supports can be used:

   (a) Solid supports for machined surfaces

(b) Adjustable supports - single contact - manually adjustable support for rough surfaces

(c) Equalizing supports - double contact support - adjusted automatically for rough surfaces

(d) "Floating Ball" support [Boyes (1982)] for castings, forgings etc on their irregular shapes and surfaces as shown in Fig. 2.9 and Fig. 2.10.

2. **Locating from internal diameter**

In this case location is done from holes or hole patterns and this method is very efficient and accurate. Various device in use are:

(a) Screw, dowel or mounting shank.

(b) Pin type bushings and locators e.g. conical locators and diamond pin locators.

3. **Locating from external profile:**

These are basically fixed stop locators. Various locators currently in practice are:

(a) Rest buttons, adjustable locators, sight locators, nesting or cavity locators.

(b) Vee locators for cylindrical workpieces, as shown in Fig. 2.11.

2.4 DESIGN OF CLAMPING DEVICES

The function of any clamping device is that of applying and maintaining sufficient counteracting holding force to a workpiece to with stand all tooling forces. Proper clamp design, based

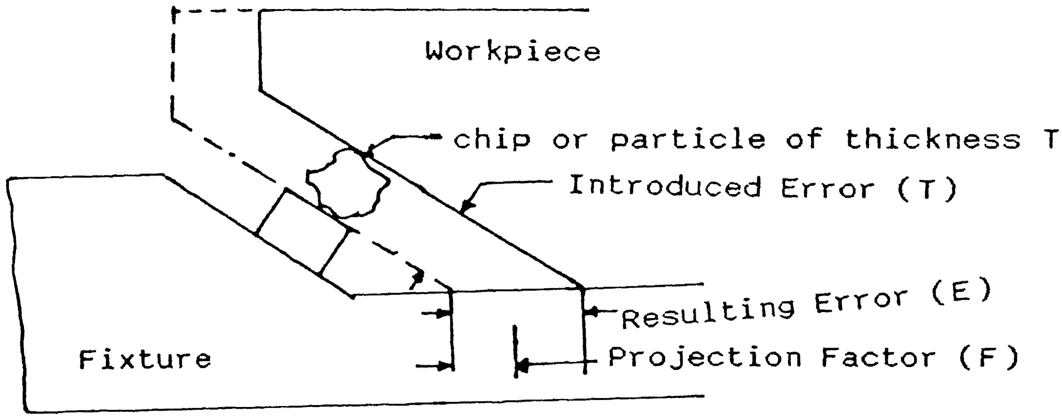


Fig 2.8 Magnification and Projection of error

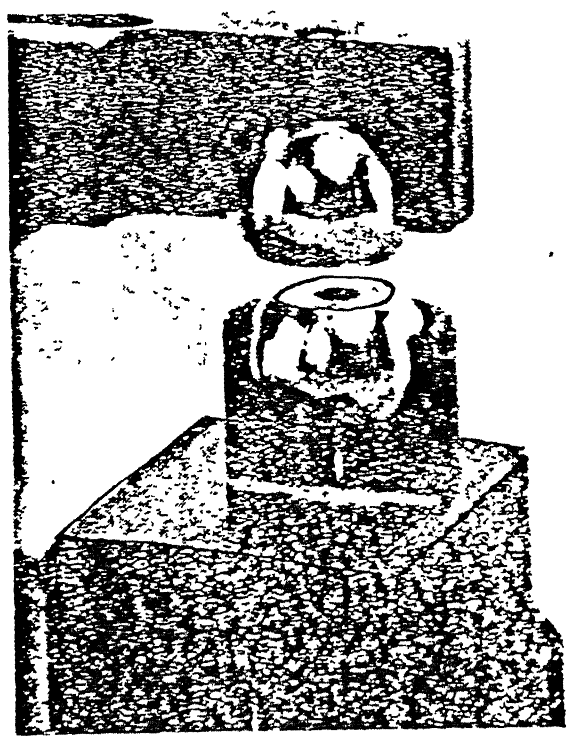


Fig 2.9 Cut-away model of a production strap clamp [Boyes (1982)]

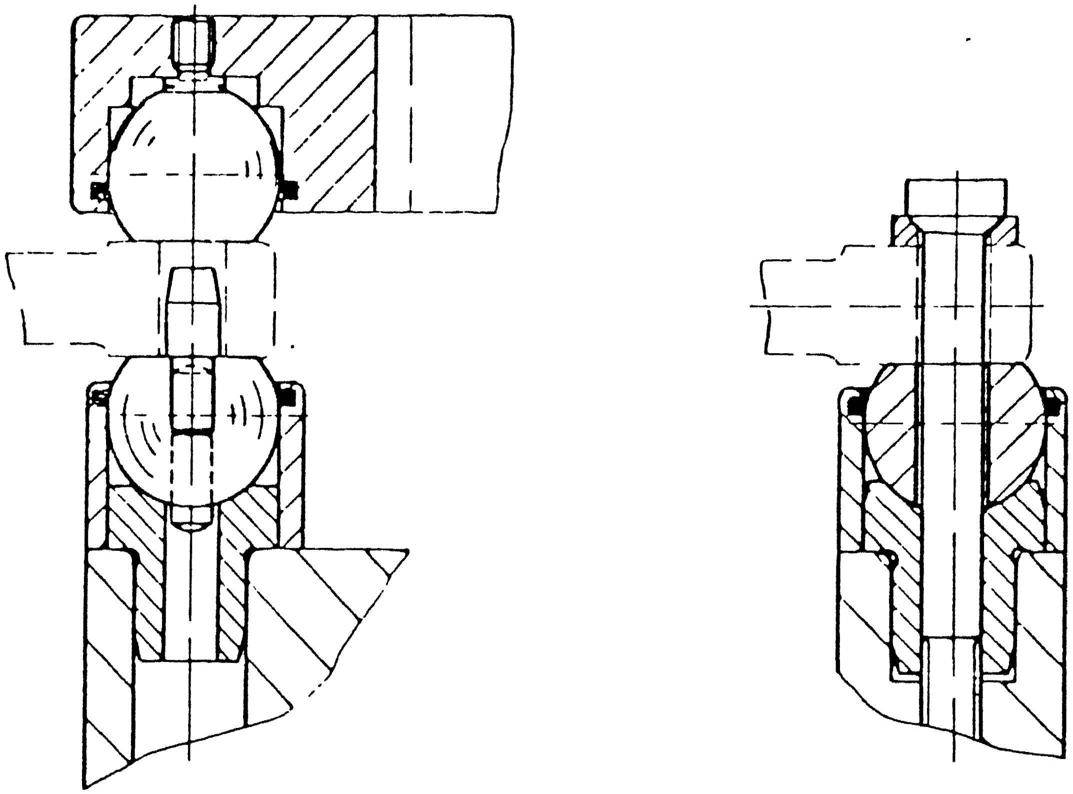


Fig 2.10 Floating Ball Support [Boyes (1982)]

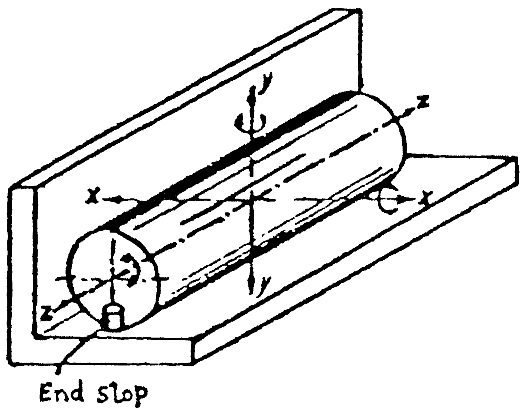


Fig 2.11 Seven degrees of freedom arrested by V locator with stop pin

upon simplicity with utility, affects total tool and product costs and permits optimum production, surface finish and tool life. Clamp selection is predicated upon analyses of the workpiece, the operation on it, and the quantity of parts to be produced.

2.4.1 CLAMP DESIGN CONSIDERATIONS

Clamp design considerations should include its location in the fixture to achieve the following purposes.

1. Clamping pressure should be directed to supported and/or rigid positions of the work so as not to distort the workpiece.
2. Loading and unloading should be easily facilitated.
3. It should maintain required workpiece relation to locators, gages and tools.
4. It should provide minimum hazards to operator, workpiece, fixture, and tool before, during, and after the work cycle.
5. It should be incorporated as an integral part of the fixture.

2.4.2 PRINCIPLES OF CLAMPING

Various principles are:

1. Clamp should always contact at most rigid point and support must be provided on the opposite surface lest it damage the workpiece.
2. All the cutting forces should be directed towards the locators or the tool body. Clamping device should not be expected to absorb the cutting forces.

3. There should not be any interference with the machine tool or the fixture.
4. The direction of the clamping force must also be considered with reference to the effect on the workpiece. The clamping force should be directed toward the solid locators and in a manner to keep the workpiece in the fixture.
5. The clamping force must hold the workpiece rigidly and firmly in contact with locating pins of surfaces.
6. The time required to loosen the clamp on the workpiece and tighten it again on next piece should be minimum.
7. Clamping pressure should not be directed toward a cutting operation but should wherever possible be directed parallel to it.

2.4.3 TYPES OF CLAMPS

Clamping devices are broadly classified into two sections:

(a) **Direct clamping devices:** They act directly on the surface of the workpiece to hold it in its place.

(b) **Indirect clamping devices:** They transfer the holding force through levers or similar devices to apply the required clamping force.

Comparison:

1. Indirect clamps apply more force
2. Indirect clamps are less affected by the vibration of the machining operations.

3. Indirect clamps can be used to move the position of the clamp actuator away from the machining area, thus allowing safer operations.
4. Direct clamps have fewer parts and their operation is simple.
5. Direct clamps require less space than indirect ones.
6. Direct clamps are more sensitive to human touch.

Clamps depend upon (a) workpiece size (b) workpiece shape, and (c) machining operations.

Criteria for clamp choosing are: Safety, efficiency, simplicity, ease of operation, and holding force.

All clamps are variations of the following basic types: strap, screw, wedge, cam, toggle, or rack and pinion. Clamping forces can be transmitted by screws, cams, levers, or wedges and by rack-and-pinion, electrostatic, magnetic, or vacuum devices. Actuation can be manual, e.g., with a wrench, key, lever, crank, or it can be automatic.

Fig. 2.12 shows mechanical methods of transmitting and multiplying force.

Fig. 2.13, and 2.14 show commercially available fixture / clamp components.

Fig. 2.15 to 2.23 show various types of clamps.

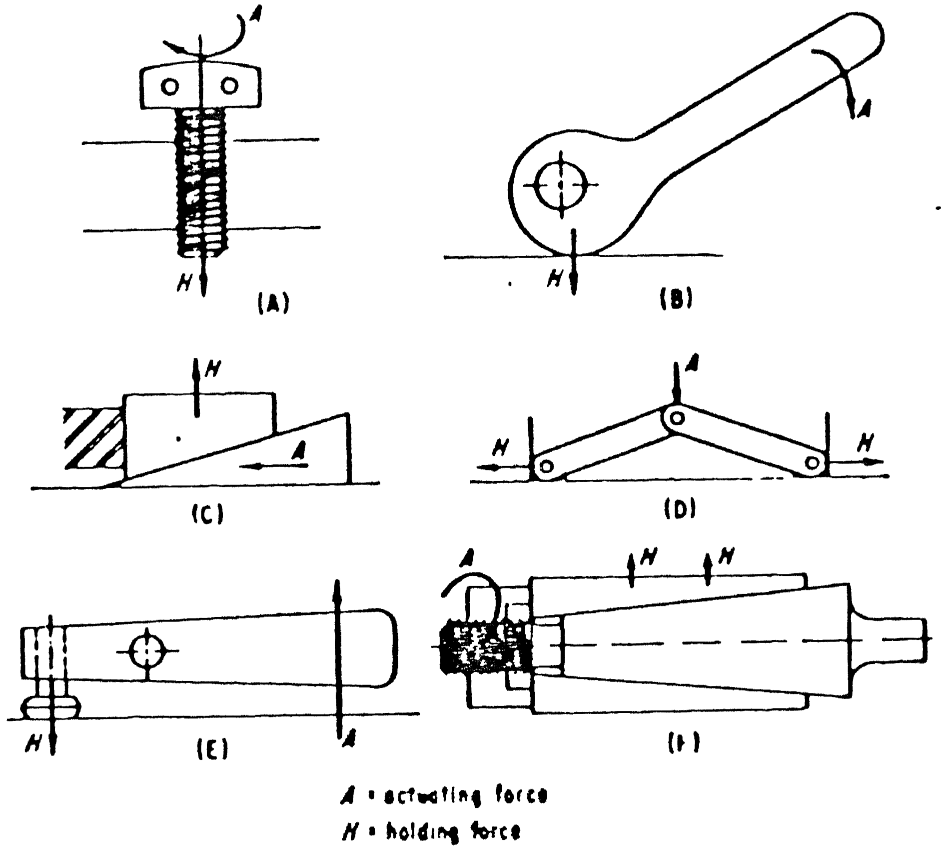


Fig 2.12 Mechanical methods for transmitting and multiplying force: (A) Screw, (B) Cam, (C) Wedge (D) Toggle linkage (E) Lever (F) Combined Screw and Wedge. [ASTME (1987)]

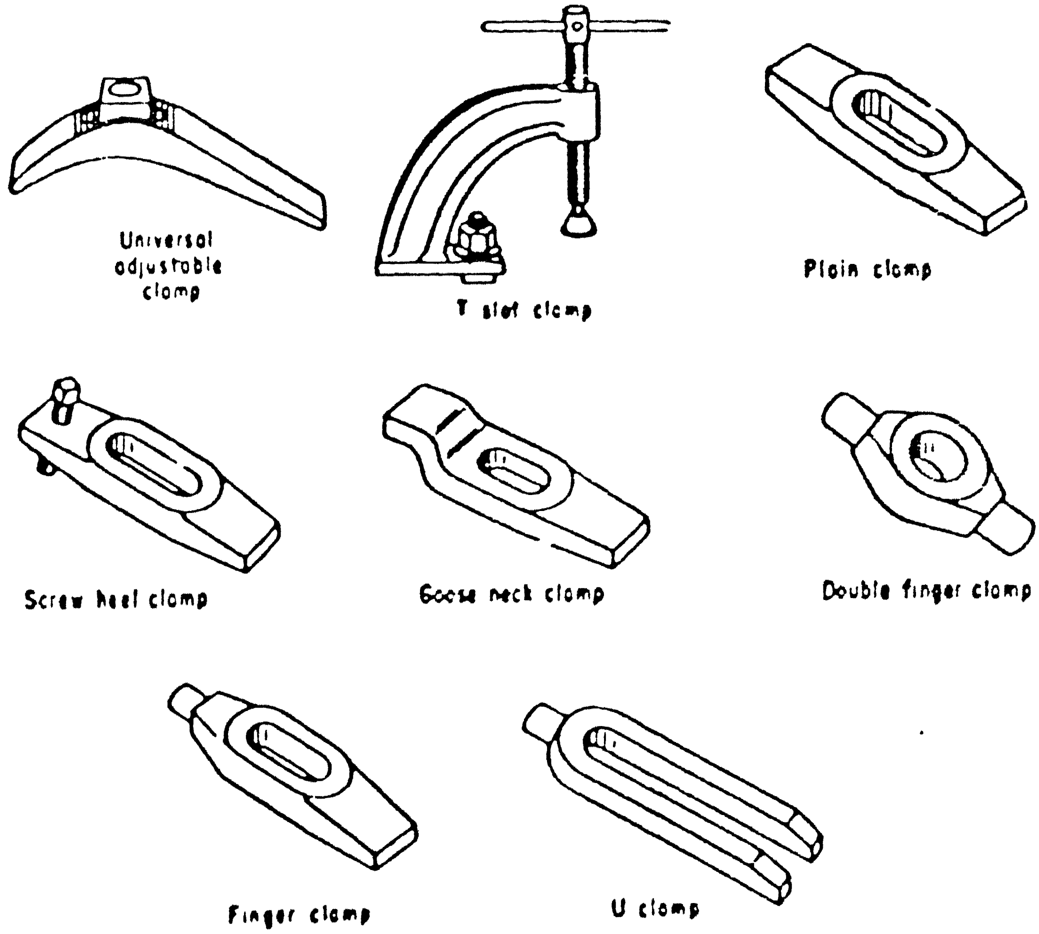


Fig 2.13 Commercially available fixture components [ASTME (1987)]

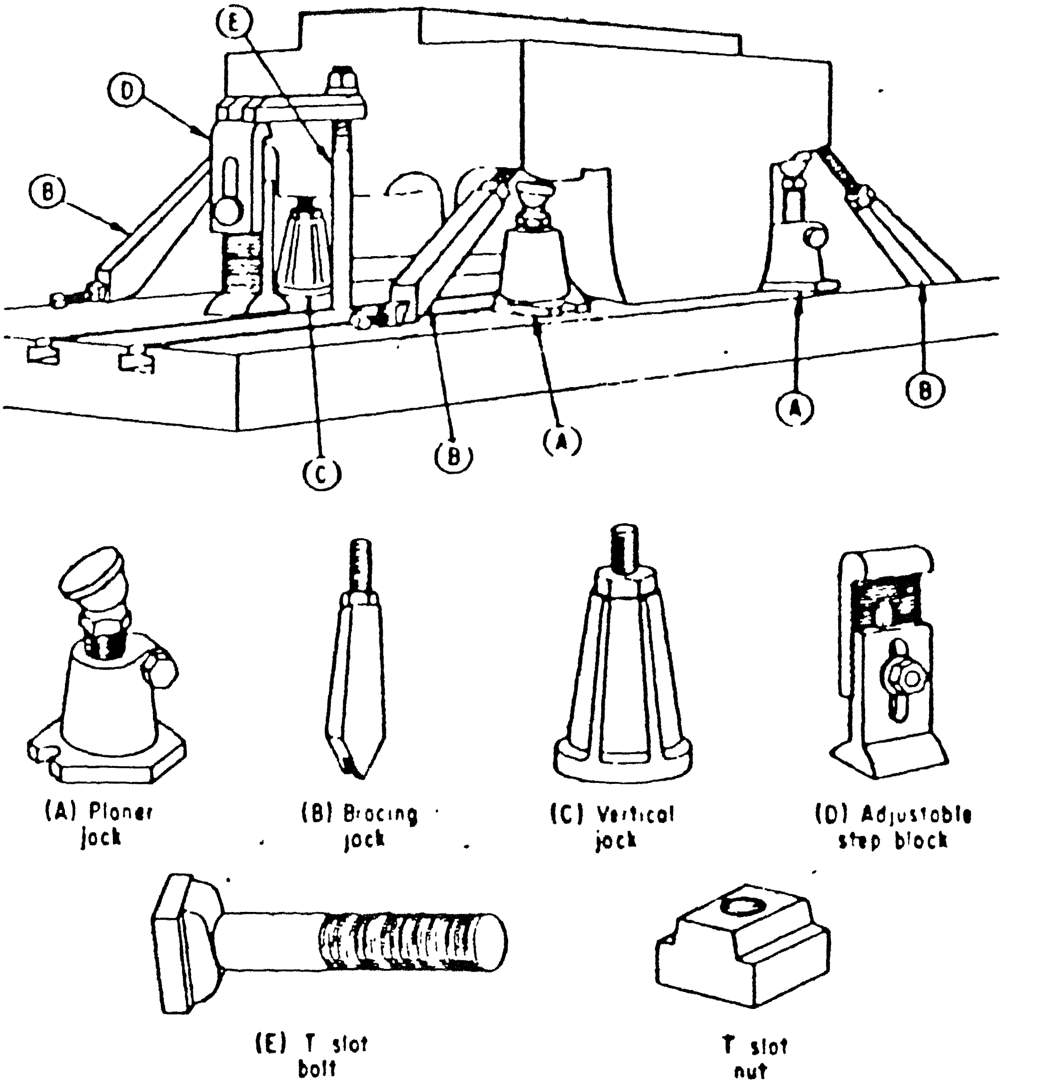


Fig 2.14 Commercial Components used to hold a large workpiece [ASTME (1987)]

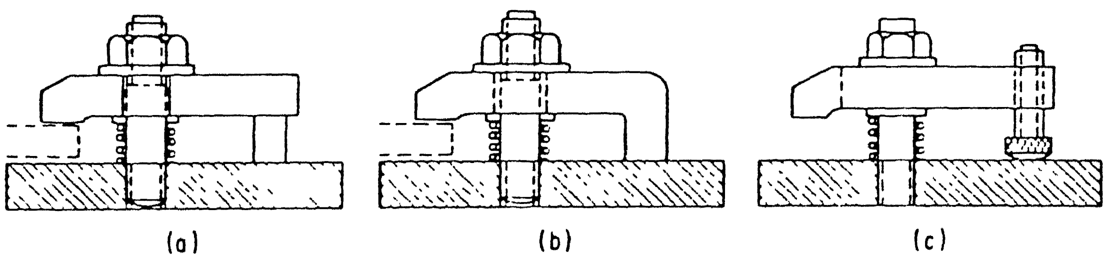


Fig 2.15 Strap-clamp design [ASTME (1962)]

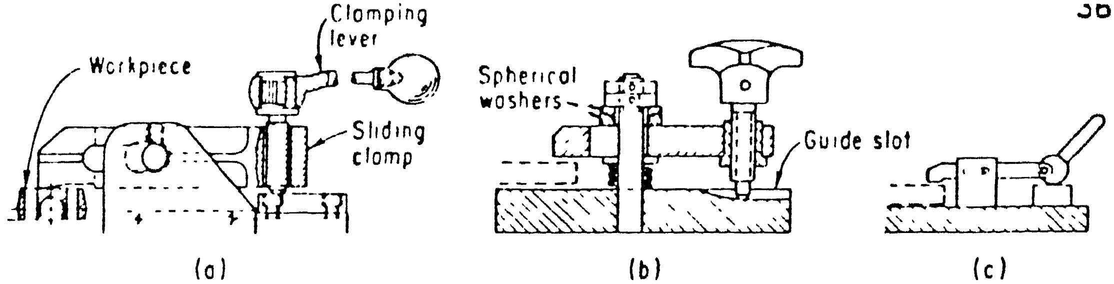


Fig 2.16 Slide clamps [ASTME (1962)]

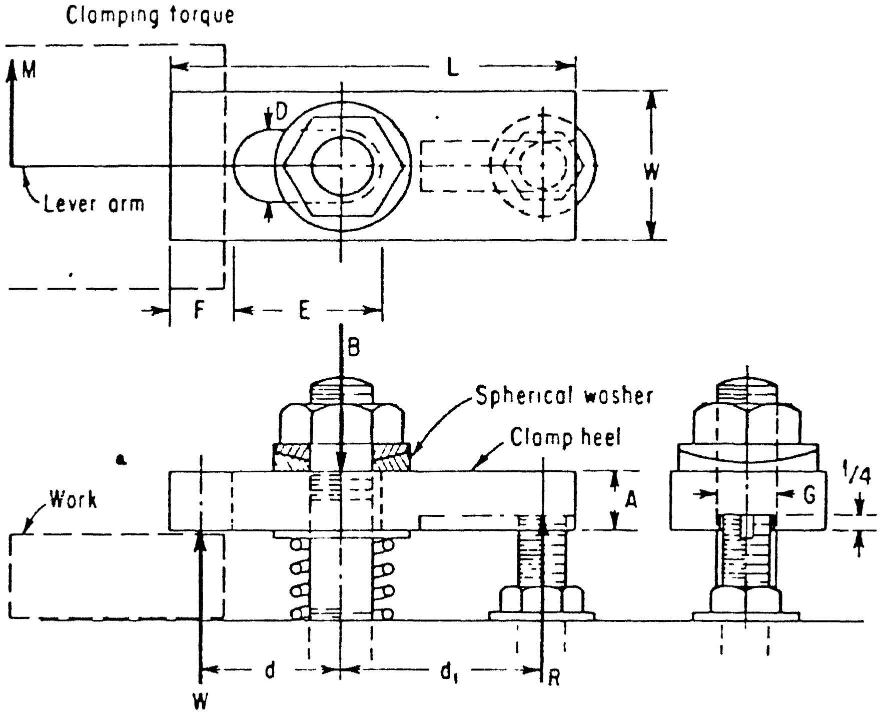


Fig 2.17 Sliding clamp design [ASTME (1962)]

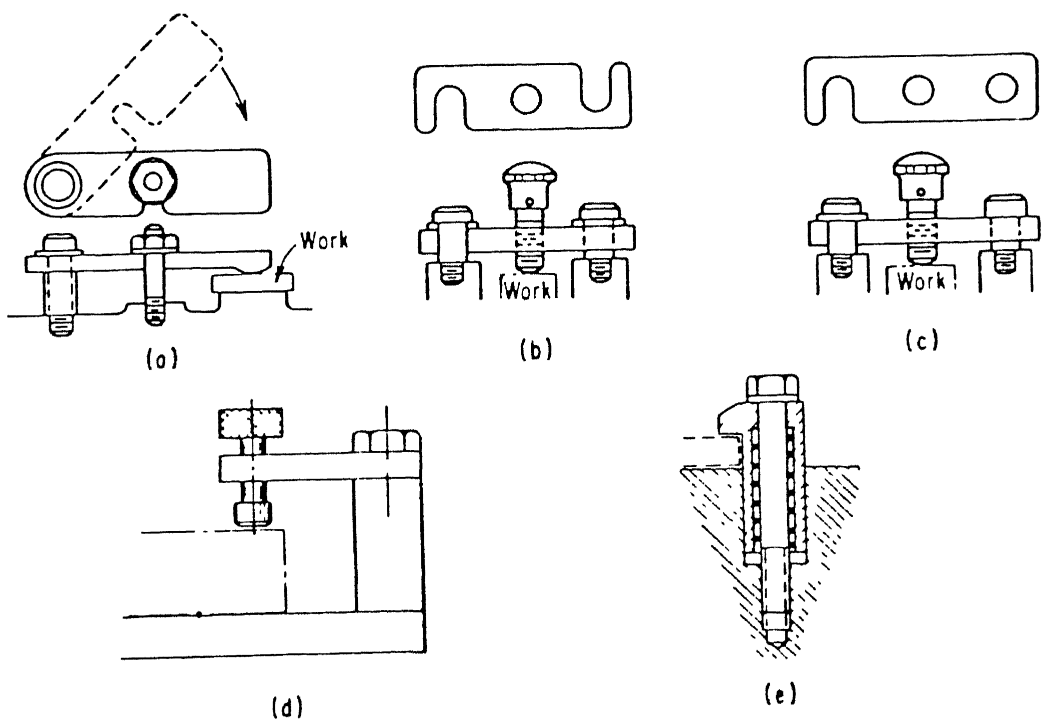


Fig 2.18 Swinging Clamps [ASTME (1962)]

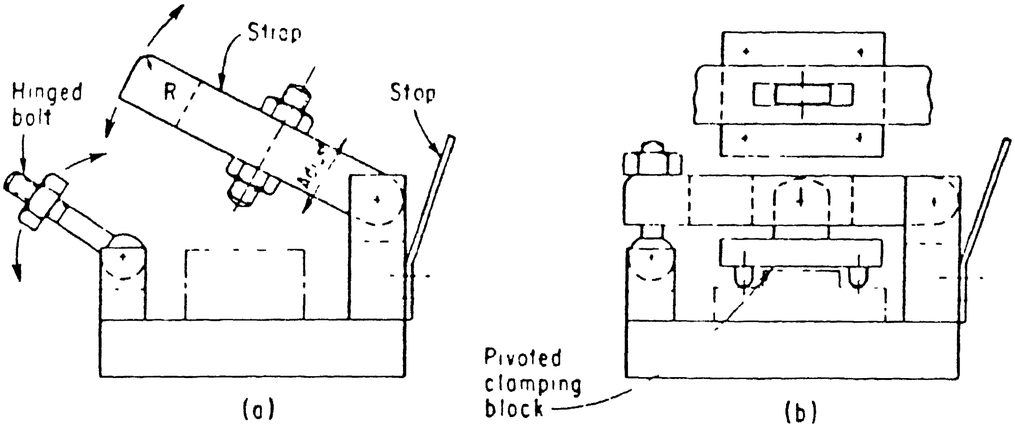


Fig 2.19 Hinge clamps [ASTME 1962)]

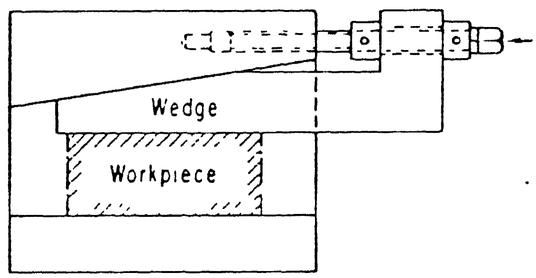


Fig 2.20 Wedge Clamp [ASTME (1962)]

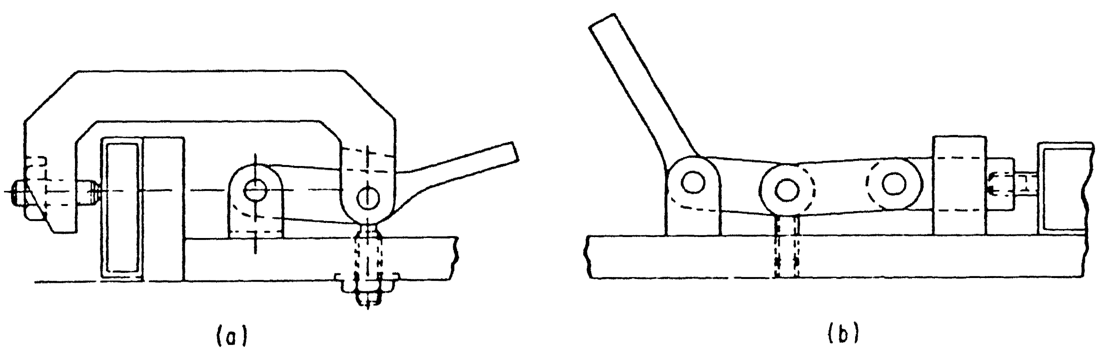


Fig 2.21 Toggle Clamps (a) C-frame type;
(b) pusher type [ASTME (1962)]

CHAPTER 3

LITERATURE SURVEY

As mentioned earlier, automating fixture design and integrating it with process planning is one of the important activity in automating the process planning. Somehow, very little attention seem to have been paid in this direction. The fixture design has been traditionally carried out using thumb rules. Its engineering analysis is quite complex and involved. Recently some work is reported in this area but most of them lack comprehensiveness. Most of the research efforts are just improvisation and automating in one or more directions, and of one or more aspects. Research efforts in the field of fixture design can be broadly classified in six areas:

1. Analytical approach
2. Experts systems for fixture design
3. Feature based design of fixtures
4. Setup planning and fixture design
5. Modular fixturing systems
6. Other related work

A brief review of these is presented in the following subsections.

3.1 FIXTURE DESIGN: AN ANALYTIC APPROACH

In this area, the mathematical modelling and optimization are used for the analysis and synthesis of fixture design. The

approach is generative as the design of fixture(s) is created after analysis and synthesis rather than evaluating and modifying some given design.

Asada and By (1985) described the basic concept of an adaptable fixturing system and its hardware implementation. The approach employs reconfigurable fixturing elements that are used to locate and hold various workparts for automatic assembly. The condition for a fixture layout to locate a given workpart uniquely at a desired location is derived. Fixture configurations change automatically based on the workpart geometry and the assembly operations required. They have developed analytic tools for designing fixture layouts. Kinematic modelling, analysis, and characterization of workpart fixturing are further discussed. Accessibility and detachability conditions are also obtained in order to guarantee that the unclamped fixture is accessible for the workpart and that the workpart can be detached from the fixture without any conflict to the fixture elements.

Chou, Chandru and Barash (1989) developed a mathematical model for automatic configuration of fixtures for prismatic parts drawing on screw theory and engineering mechanics. Analysis of deterministic workpiece location, clamping stability, and total restraint and synthesis of determination of locating and clamping points on workpiece surface and determination of clamping forces is actually performed.

DeMeter (1994) showed how to apply restraint analysis to a fixture which relies on frictionless or frictional surface contact. With the help of linear programs using static

equilibrium, constraints models of Wrench system are developed, by them.

King and Hutter (1993) built an optimization model on the foundation of kinematic, force, and robotics grasp analysis. The criteria of maximum stiffness, resistance to slip, and stability are validated by the generated fixture design.

Lee and Cutkosky's (1991) fixture planning module employed symbolic and numerical analyses for analyzing fixture kinematics and clamping forces. Including the analyses of friction. Limit surfaces in force/moment space are introduced to check whether parts will slip and to help in specifying clamping forces.

Lee and Cho (1994) considered three kinds of constraints such as geometric, kinematic, and force constraints to provide an appropriate fixturing system. The use of limit surfaces, obtained either by scanning over the space of possible motions or by Minkowski sums is compared with other approaches to establish the relationships among applied forces and moments and corresponding direction of sliding motion.

Menassa and DeVries (1989) developed six rules to select secondary and tertiary locating datums and then these kinematic rules are used to determine the position of the locating points in fixture design.

Menassa and DeVries (1991) proposed optimization techniques in the design of fixtures. Using the minimization of the workpiece deflection at selected points as the design criterion, they determined the positions of the fixture supports. The Finite Element Method is used for calculating deflections, and

Broyden-Fletcher-Goldfrab-Shanno optimization algorithm is used to determine fixture support positions.

Sayeed and DeMeter (1994) developed a software and uses the analysis facility of the software to satisfy kinematic restraint, total restraint, and tool path clearance requirement. The basic geometry of the fixture is specified in a series of steps. In addition the lower bounds on required clamp actuator intensities are also determined, by the proposed software.

Trappey and Matrubhutam (1993) presented a set of algorithms to determine the fixturing locations considering orientation and geometry of a non prismatic workpiece with the application of projective geometry.

3.2 EXPERT SYSTEMS FOR FIXTURE DESIGN

The research efforts in this category of fixture design lead to various expert system rules and/or Object/Rule based automated fixture design systems.

Darvishi and Gill (1990) developed four modules of fixture design expert system (FDES) which are fixture selection rules, reference plane selection rules, generic element selection, and selection of standard elements.

Kumar, Nee and Prombanpong (1992) developed rule/object based approach to group the machining features, recognized by a feature recognizer, into appropriate fixture setups. The approach also recommends suitable clamping, locating and supporting points.

Nee and Kumar (1991) presented a framework for automated fixture design using a solid modeler, an object/rule based expert system and X window.

Ngoi and Leow (1994) developed a software comprising a knowledge-based Adviser - which assists the tool designers in selecting components from a Modular fixturing system (MFS), a fixturing component assembly program and a CAD system.

Pham and Lazaro (1990) developed AutoFix, a fully automated CAD package for configuring complex fixtures from a database of modular elements. The program also designs special elements if standard ones are non existent. AutoFix also uses Finite Element Analysis to compute the deflection of the fixtured workpiece and determine the optimum position of supports.

Roy and Sun (1994) developed heuristic algorithms for selecting the locating and clamping positions for an automatic fixture design (AFD) system.

Siong et al. (1992) described the recent trends in the integration of knowledge-based and 3D solid CAD techniques for modular fixture design, pricing and inventory control. MOFDEX, a 3D Modular Fixture Design Expert System is developed for the purpose.

3.3 FEATURE BASED DESIGN OF FIXTURES

Process and operation planners manually recognize the existence of holes, slots, pockets and other features in the product drawing, and plan the machining of each of these features.

Features are generally defined as entities with attributes of both form and function. There is a loose correspondence between features and machining operations e.g. holes may be drilled, reamed or bored, but they are not milled. So it is very helpful in automating machining planning to have a description of the product in terms of features. The description of the product in terms of features is often called feature-based model. In today's CAD, a complete product model exists mostly in the form of a 2D drawing and sometimes in the form of a solid model and much less frequently in the form of a feature-based model. The dominance of 2D drawing will not change soon since a 2D drawing contains so much information concisely and it is so convenient. It is desirable that a computer program interprets a 2D engineering drawing and generates a feature-based model and a solid model [Sakurai (1990)]. Less desirable but still desirable is a computer program which recognizes features in a solid model of the product as human planners recognize features in a 2D drawing.

Dong, DeVries and Wozny (1991) investigated the use of features for fixture design, concentrating on the selection of locating elements and the identification of locating surfaces for workpiece positioning. Feature based representation for machined and intermediate workpieces for selecting locating and supporting surfaces is the prime achievement of the work.

Kumara et al. (1994) proposed super relation graph (SRG) method for extracting shape features. Hypotheses were generated from a combination of 'graph-based' and 'neural network' approaches and these hypothesis were verified using computational

geometry techniques.

Liou and Suen (1992) presented a prototype feature-based fixture planning system for flexible assembly. By representing the geometric and non-geometric properties of fixtures and workpieces in terms of features, a fixture process planning system can be implemented using a knowledge-base approach.

Nee et al. (1992) presented a feature based classification scheme for fixtures using a 3D solid modeller, a feature extractor and an object-oriented expert system shell.

Requicha and Vandenbrande (1988) provided an excellent survey of research on feature recognition, operation selection and sequencing, and operation planning.

3.4 SETUP PLANNING AND FIXTURE DESIGN

This areas of automating process planing has been, so far, not well researched. The intricacies involved, have led to only a few research efforts on setup planning. Infact, automatic setup planning and fixture design is the field where still, a lot has to be done.

Boerma and Kals (1988) and (1989) proposed FIXES a planing procedure, consisting of two distinct parts (1) the selection of setups and (2) the design of a fixture for each set-up. The automatic selection of set-ups is based on the comparison of the tolerances of the relations between the different shape elements of the part. Then based on both the topology of the prismatic part and the geometric relations between different part elements,

automatic selection of the faces for the positioning, clamping and support of workpieces is done.

Chen and Leclair (1994) proposed an unsupervised learning algorithm to categorize features into a setup for machining. The proposed algorithm and architecture incorporate multiple objective functions into the setup generation.

Sakurai (1990), (1992) and Sakurai and Gossard (1991) proposed automatic setup planning and fixture design with the help of algorithmic and heuristic methods. Representation of toleranced solid model of the finished component, and intermediate workpiece geometry, and feature-based models are the side products of the research effort.

Young and Bell (1991) proposed a method using machine capability representations and product model analysis techniques to integrate fixturing strategies with technological and geometric information, within a product modelling environment, to automate set-up planning for machining.

3.5 MODULAR FIXTURING SYSTEMS

With the advent of flexible manufacturing system (FMS) and the concept of automation of factories, modular/reconfigurable fixtures are the ones, which are capturing the researchers eyesight. The following portion of the subsection highlights the research efforts in the this particular area.

Benhabib, Chan and Dai (1991) developed a modular programmable fixturing system (MPFS) for robotics assembly with

some built in flexibility. The achievements of this system are: modularity, automatic reconfigurability, sensory feed back controllability, and programmability.

Giusti et al. (1991) described about a prototype plant for the robotized assembly of modular fixtures for NC machining centers.

Horie (1988) described the outline of a building-block-type modular fixturing system "BLOCK BUILD JIG SYSTEM 64" and discussed its adaptability to factory automation and its future applications.

Shirinzadeh (1993) proposed the design of reconfigurable fixture modules for robotics assembly.

3.6 OTHER RELATED WORK

Bidanda and Rajgopal (1990) proposed an algorithm based on dynamic programming for selecting the optimal sequence of work holding devices for manufacture of rotational parts in order to minimize the total work holding time.

Chang (1992) discussed the major issues to be considered in fixture planning for machining processes and presented a rationalized approach to computer-assisted fixture planning (CAFP).

Hargrove and Kusiak (1994) presented an excellent review of some of the current developments in the area of computer-aided fixture design (CAFXD) and proposed some directions for future research initiatives.

Jiang et al. (1988) developed a computer-aided Group Technology fixture design system (CAGFD) based on the concept of fuzzy mathematics.

Schreiber (1991) discussed about clamp actions, types of clamps and part tolerance in fixture design.

Thus, one can find that most of the research efforts are, indeed, genuinely in the direction of complete automation of machining planning. Still a lot is left to achieve the objective. The field of fixture designing carries a lot of offshoots and different research projects are going on, trying to tackle these offshoots, either analytically or with the help of expert systems. Feature recognition and modular fixturing are two widely recognized tools to help achieve automatic fixture designing. Looking at the trend, one can easily predict that time is not far away, when total integration between computer-aided design (CAD) and computer-aided manufacturing (CAM) will be achieved.

CHAPTER 4

DESIGN OF FIXTURES: A STRUCTURAL APPROACH

With the advent of flexible manufacturing systems (FMS) the need for the development of a flexible fixture design system is greater than ever. In an FMS, the investment in fixturing can be as high as 20% of the total investment cost [Siong et al. (1992)]. As many industries are moving towards the 'zero part inventory' system to achieve better cost control, the use of dedicated workholding fixtures is becoming less productive. It is now necessary to develop a flexible computer aided system which can synthesize and analyze setup plans, and design a cost effective workholding method for any given part in a rapid manner [Sayeed and DeMeter (1994)].

4.1 APPROACHES IN FIXTURE PLANNING AND DESIGN

Fixture planning, similar to process planning, consist of both macro and micro aspects of planning. The *macro aspect* of planning involves determination of the required operations and their sequence (for process planning) or the required setup positions and orientations of the workpiece and their sequence (for fixture planning). The *micro aspect* of planning determines the specification of each individual processing step (operation) or, for fixture planning, the components and the layout of the fixture for each individual setup position [Chang (1992)].

Similar to computer-aided process planning (CAPP) fixture design can be approached using the variant and generative fixture design techniques [Nee and Kumar (1991)].

In *variant* fixture design, workpieces belonging to the same part family are assumed to have similar machining features and/or requiring similar operation sequences and setups. In this approach, a fixture and workpiece classification and coding system has to be formulated. It is also necessary in this to include information on cutting tools, machine tools, positioning and dimensioning tolerances with respect to location and datum surfaces, method of securing the workpieces and their loading sequences, assembly sequences, coolant and chip disposal considerations etc.

A *generative* fixture design approach is used when similar fixture designs cannot be retrieved. The information needed to design a fixture using this approach includes workpiece information, process plan, machine and cutting tool envelopes, fixture element and related machining libraries. This information is passed to an *expert generative fixture design system* consisting of machining physics, which includes formulae for evaluating cutting forces, stability, strength analysis, deflection of structural members etc. and expert heuristics, such as correct proportioning, ease of loading, rule of thumb, safety considerations, ergonomics, ingenuity in securing workpieces etc. The final output consists of detailed parts and assembly drawings.

4.2 FIXTURE DESIGN: A BROADER PERSPECTIVE

The fixture design process can be divided into three phases [Chou et al. (1989)].

- Fixture planning
- Functional configuration
- Fixture construction

In general, a workpiece may require more than one fixture for its machining. The task of *fixture planning* is to determine the number of fixtures needed, the types of fixtures, the orientation of the workpiece in each fixture, and the machining operations to be executed in each fixture.

The task of *functional configuration* is to layout a set of locating and clamping points on workpiece surface such that the workpiece is completely restrained. It involves, analysis and synthesis of fixtures.

The task of *fixture construction* is to select fixture elements to construct a fixture body to support the workpiece and to hold the fixture elements together.

Fixture design is a very complex process. It needs the knowledge of quantitative methods which can be used to calculate cutting forces, deflection of fixture elements, tolerance analysis, interference analysis, stability analysis etc. However, many of the good design features of fixtures are synthesized from the knowledge of cutting tools, machine tools, positioning and dimensioning tolerances, feature interactions, locating and clamping hardware (and their capacity), clamping and

locating placement techniques, method of securing workpieces and their loading sequences, machining operations and its sequence, assembly sequences, coolant and chip considerations etc. [Roy and Sun (1994)].

4.3 MODULAR FIXTURES

A fixture is a special tool used for locating and firmly holding a workpiece in the proper position during machining. It is a special tool in the sense that each tool, generally, designed and built specifically for making one part only even though the functional requirements are always the same. Due to specialized nature of these tools, their designs are as varied as the part which they are to serve. A fixture is composed of several kinds of components. They are locators, clamps, supports and the body. Locators are positioned in a fixture in such a way that the workpiece will be located accurately in relation to the machine coordinate frame when it is in contact with all the locators. Clamps generate and direct the acting forces in such a way that the part is securely locked in its place. Supports are positioned, generally, below the part to establish the location of the workpiece on its vertical or Z axis, while locators are placed on two peripheral edges and locates the work piece along horizontal or X and Y axes [Ngoi and Leow (1994)]. Supports are mainly used to support a workpiece when it may deform under clamping or cutting forces. The body of a fixture hold these components together. Though a variety of standard and commercial

fixture components are available for use in building a fixture, still a fixture has to be designed and built for each part to accommodate the unique shape of the part. Since designing, machining and building a fixture takes time, it is another cause of inflexibility in flexible manufacturing system.

Modular fixturing systems are said to have the potential to solve this problem of inflexibility. A modular fixturing system consists of many different fixturing components that are assembled in different combinations to construct a large number of different fixtures. Fig 4.1 shows a typical modular fixturing system and fig 4.2 shows the base plate and angle plate on which such modular fixtures are built. Grid-bases have a grid of holes which are used to locate and attach other fixtures components accurately and firmly. Since assembling a fixture will take only a few hours, a modular fixture system offers flexibility.

4.4 REQUIREMENTS FOR FIXTURE

A fixture is a special tool used for locating and firmly holding a workpiece in the proper position during machining [ASTME (1962)] [Houghton (1956)] [Jig (1957)]. A fixture must satisfy the following five requirements.

1. Accurate locating of the workpiece
2. Total restraint of the workpiece
3. Limited deformation of the workpiece
4. No interference between fixture components and cutting tool
5. "Goodness" of design

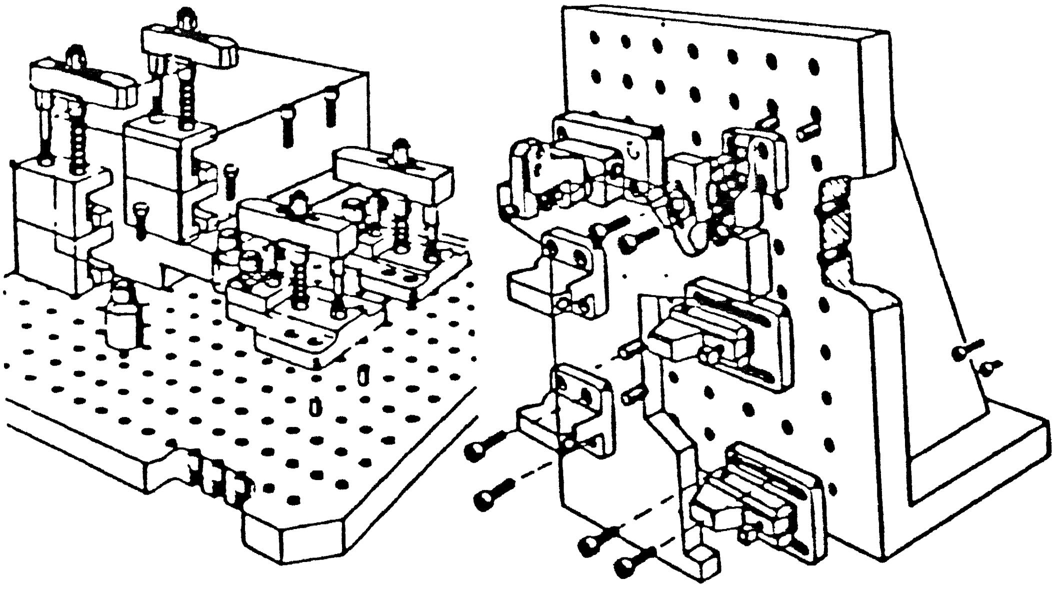


Fig 4.1 Examples of modular fixtures

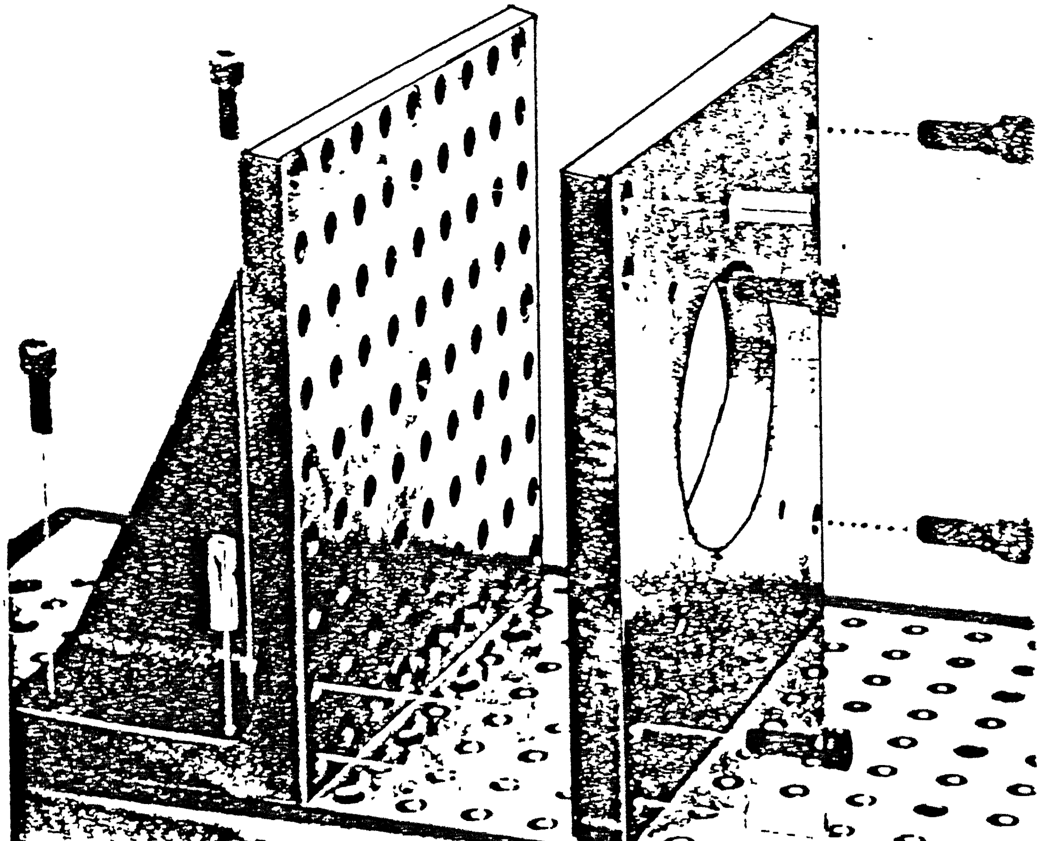


Fig 4.2 Baseplate and Angleplates [Boyes (1982)]

4.4.1 ACCURACY OF WORKPIECE LOCATION

Due to the closed loop measuring system and greater rigidity in the structural members, NC machines have greater accuracy and precision than conventional machines. To realize this accuracy in the finished part and ensure that the finished part satisfies its tolerance specifications, a fixture must locate the workpiece accurately in relation to the NC machine coordinate.

The requirement for locating is to align the part coordinate system attached to the reference faces to the machine coordinate system very accurately. Once the workpiece is located accurately, the desired features are created by the cutting tool, as it moves along the path prepared by the operation planner. The locating accuracy directly affects the accuracy of the features created.

The are five issues concerning locating accuracy. They are:

(1) Deterministic Locating

When the workpiece is settled against the locators, the position of orientation of the workpiece must be determined. This can be expressed equivalently as the workpiece cannot slip with respect to any locators while staying in touch with all the other locators.

(2) Practice in Dimensioning and Tolerancing

Since a part can never be machined perfectly, designers specify tolerances on part drawing. Tolerance is the maximum allowable deviation of a feature from its ideal geometry in size, location, form and orientation. The current practice in dimensioning and tolerancing must be reviewed since it is tightly

related to accurate locating.

(3) Required Locating Accuracy

Since the purpose of locating a workpiece accurately is to create features within their dimensional tolerances, the required locating accuracy for a feature has to be determined from the tolerance specifications of the feature [Sakurai (1990)].

Locating is an effort to make the part coordinate system (defined by datum features) coincide with the machine coordinate system. Locating error of the workpiece is defined as the discrepancy between the two coordinate systems. The calculated locating error of the feature must be related to the given tolerances of the feature.

(4) Causes of Locating Error

The causes of locating error must be identified to find out their impact on locating error. These errors may be due to locators or locating faces or even due to location with non-datum features.

(5) Calculation of Locating error of Workpiece

A method must be developed to calculate the locating error.

4.4.2 ADEQUATE RESTRAINT OF THE WORKPIECE

Fixture must restrain the workpiece from moving when the workpiece is being machined and undergoes cutting forces and torques. It it moves, the accuracy of the finished part will be lost. Hence, kinematic analysis of the workpiece is required to check that it has no degree of freedom. Therefore, force and

moment equilibrium analysis is required to calculate necessary clamping forces to prevent the workpiece from moving under the cutting wrenches.

4.4.3 LIMITED WORKPIECE DEFORMATION

A workpiece undergoes elastic deformation during machining. This elastic deformation is released when the cutting tool moves away from the workpiece or when the workpiece is unloaded from the fixture, and the geometry of the workpiece changes by the amount of released elastic deformation causing inaccuracy in the finished part geometry. Since a workpiece is an elastic material and formidable clamping forces and cutting forces are applied to, elastic deformation is unavoidable. But it has to be limited to some acceptable magnitude to satisfy tolerance specifications by changing clamping positions and adding supports if necessary. Workpiece deformation is not numerically estimated at all both in the current machine shop practice and in the literatures on fixture design. A fixture designer put supports based on his experience and instinct.

There are four issues in considering acceptable workpiece deformation.

(1) The critical workpiece deformation models must be identified e.g. deformation is bending in larger than deformation due to compression for a given load [Ryder (1969)].

(2) For each deformation mode, the maximum acceptable deformation must be determined from the tolerance of the features.

(3) A method to estimate workpiece deformation under cutting forces and clamping forces has to be developed.

(4) A method for finding the critical cutting forces must be developed.

4.4.4 ABSENCE OF INTERFERENCE

There should be no interference among the workpiece, fixture components and the cutting tool movement path. There are two basic approaches in this direction. The first is *Configuration space approach [Zeid (1991)]*. In this approach, the space which an object can occupy without interfering with other objects is calculated first. Then the position or the path of the object is determined in the space. This approach is efficient. The other is *generate and test approach*. In this approach, the position of the object to be placed is determined first without considering interference and then whether it interferes with other objects is checked. This approach can be efficient if search space is small the approach taken in this work is mainly the first one.

4.4.5 MERIT OF THE DESIGN

Satisfaction of the above mentioned requirements is not enough. Not all fixture configurations that satisfy the requirements are acceptable. The fixture configuration must be a "good" one. There are criteria which make one configuration better than another. Some of them are:

(1) Smaller number of setups

They lead to less setup time and better accuracy of the finished part.

(2) Smaller number of fixture components

For easier assembly of fixture components and easier loading of workpiece. But the number of components does not need to be minimum.

(3) Ease of loading a workpiece

A workpiece must be loaded easily and accurately.

(4) Lower profile of fixture components

This is desirable to allow the cutter a shorter retract when moving from one feature to another.

4.5 FRAME WORK FOR FIXTURE DESIGN

The algorithm for fixture design in its broadest sense can be defined as follows:

Given

Workpiece drawing, machine tool, cutting tool and operation list

Find

a method to reduce the twelve degrees of freedom of the workpiece.

Subject to

{

(1) Feasibility of certain operations

(2) Fixturing rules

(3) Fixturing components

}

Optimizing

the stability of the workpiece

4.6 FIXTURE DESIGN SYSTEM STRUCTURE

The structure of the proposed automatic fixture design system is shown in Fig 4.3. It includes four main components [Roy & Sun (1994)].

1. **An 'Informationally complete' product model.** It describes in detail the workpiece to be machined and acts as the central database for the fixture design. It contains the overall physical, geometrical and technological information of the workpiece.
2. **Knowledge Base(KB).** A knowledge of manufacturing methods, machining centre, work-holding devices, along with heuristic and algorithmic methodologies for fixture design, is stored in the knowledge base.
3. **An Inference Engine.** It controls and executes the appropriate methods (rules) towards the fixture synthesis process.
4. **Final fixture Configuration.** It ensures that the fixture configuration selected meets all the design and safety requirements.

4.7 FIXTURE DESIGN SYSTEM MODULES

The fixture design system can be broadly broken into three modules (Fig 4.4).

1. Input modules
2. Processing modules
3. Output module

4.7.1 INPUT MODULES

This lead to the creation of an 'informationally complete' product model. The synthesis process begins with a complete description of the workpiece for which a fixture needs to be designed. The input module contains information regarding

- workpiece geometric data
- process plan data
- machine tool data
- cutting tool data
- cutting path envelope data
- fixture element data

Workpiece geometric data in this research is taken in the form of B-rep, the utility and details of which ar shown in following subsection.

4.7.2 WORKPIECE GEOMETRIC DATA MODULE

A new modelling technique available to designers on a CAD/CAM system is solid modeling. The use of solid modeling in design and manufacturing is increasing rapidly because of the reduced

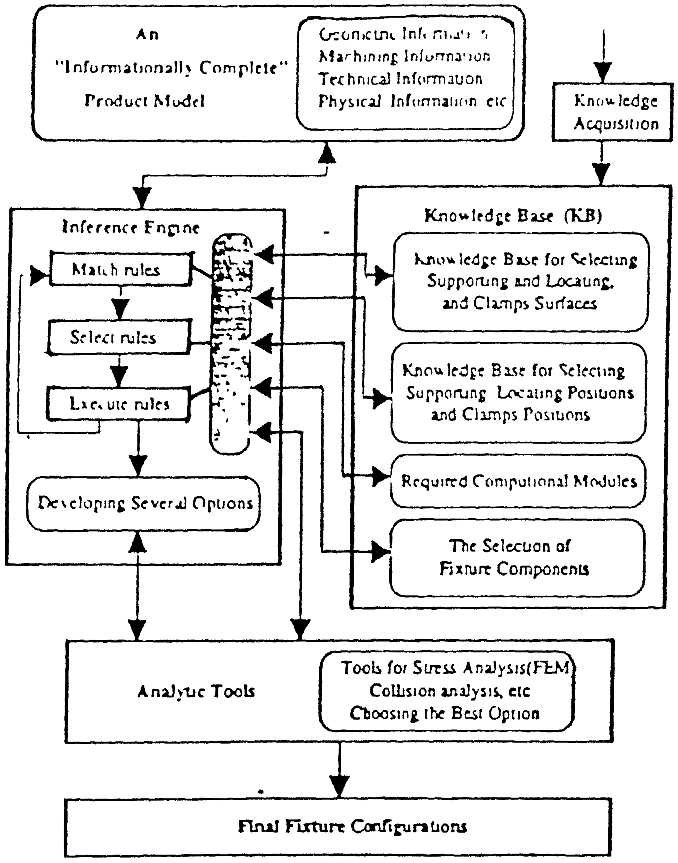


Fig 4.3 Structure of Automatic Fixture Design System [Roy and Sun (1994)]

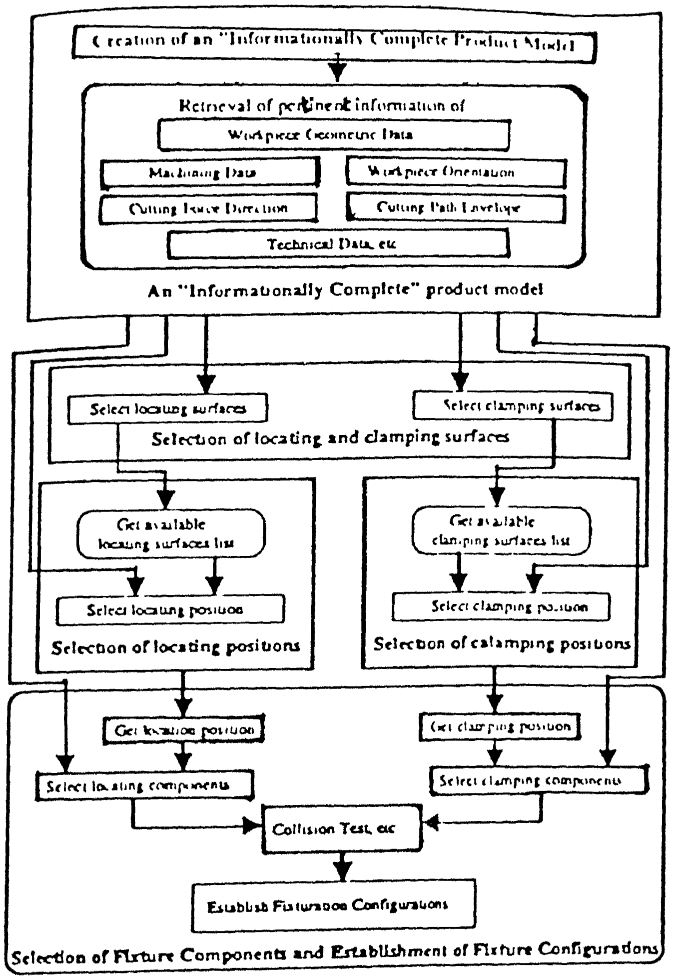


Fig 4.4 Different Computation Modules of the Automatic fixture Design System [Roy and Sun (1994)]

computational costs, fast computing hardware, improved user interfaces, increased capabilities of solid modeling itself, and software improvements [Zeid (1991)].

Solid modeling techniques are based on informationally complete, valid, and unambiguous representation of object [Hoffmann (1989)] [Mortenson (1985)]. Solid modelers store more information (geometry and topology) than wireframe or surface modelers (geometry only). The topological information it stores permits functional automation and integration. For example, the mass property calculations or finite element must generation of an object can be performed fully automatically.

The difference between geometry and topology is illustrated in Fig. 4.5. Geometry (also called metric information) is the actual dimensions that define the entities of the object. The geometry that defines the object shown in figure is the length of lines L1, L2, and L3, the angles between the lines, and the radius R and the centre P_1 of the half circle. Topology (called combinatorial structure) on the other hand; is the connectivity and associativity of the object entities. It defines neighborhood or relational information between object entities. The topology of the object shown in Fig. 4.5 (b) can be stated as follows: L_1 shares a vertex with L_2 and C_1, L_2 shares with L_2 and C_1, L_1 and L_3 donot overlap and P_1 lies outside the object.

For automation and integration purposes, solid models must be accurate and should have high speed of creation, which depend directly on the representation schemes. Each of these schemes has its own advantages and disadvantages, depending on the

application. For example, Boundary Representation (B-rep) modelers can better represent general shapes but usually require more processing time. In contrast Constructive Solid Geometry (CSG) models are easier to build and better suited for display purposes. However, it may be difficult to define a complex shape with it [Olling and Deng (1992)] [Turner et al. (1991)].

Boundary representation s one of the two most popular and widely used schemes (the other is CSG) to create solid models of physical objects. A B-rep model is based on the topological notion that a physical object is bounded by a set of faces. These faces are subsets of closed and orientable surfaces. A closed surface is one that is continuous without breaks. An orientable surface is one in which it is possible to distinguish two sides by using the direction of surface normal to point to the inside or outside of the solid model. Each face is bounded by edges and each edge is bounded by vertices.

While B-rep system stores only the bounding surfaces of the solid, it is still possible to compute volumetric properties such as mass properties (assuming uniform density) by virtue of the Gauss divergence theorem which relate volume integrals to surface ones [Zeid (1991)].

Objects that are often encountered in engineering applications can be classified as either polyhedral or curved objects. A polyhedral object (plane-faced polyhedron) consists of planar faces connected at straight/linear edges which, in turn, are connected at vertices e.g. a cube or a tetrahedron. A curved object (curved polyhedron) is similar to a polyhedral object but

with curved faces and edges instead. Polyhedral objects are shown in Fig. 4.7. In B-rep, body is a set of faces that bound a single connected closed volume. It is an entity that has faces, loops, genus, edges and vertices. A loop defines a non-self intersecting, piecewise, closed space curve which, in turn, may be a boundary of a face. The genus is the number of through holes or handles. By convention, it is taken that surface normal N is positive if it points away form the solid, Fig. 4.6.

Euler (in 1752) proved that polyhedra are topologically valid if they satisfy the following equation

$$F - E + V - L = 2\,(B - G) \qquad (4.1)$$

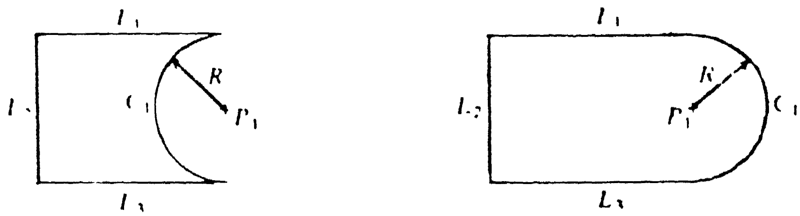
Where F,E,V,L,B and G are the number of faces, edges, vertices, loops, bodies and genus respectively. Equation (4.1) is known as Euler or Euler-Poincare Law. For simple polyhedra this equation is reduced to

$$F - E + V = 2 \qquad (4.2)$$

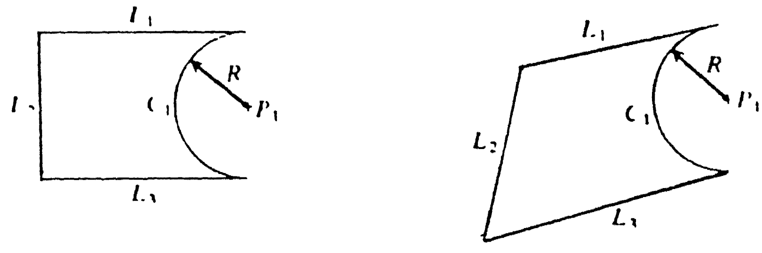
Table 4.1 shows the counts of the various variables of equation (4.1) for polyhedra shown in Fig. 4.7.

The representation of curved edges is more complex than representing piecewise linear edges. If the curved objects are represented by storing the equations of the underlying curves and surfaces, the resulting boundary scheme is known as an exact B-rep scheme. Another alternative is the approximate or faceted B-rep (sometimes called tessellation rep). In this scheme, any curved face is divided into planar facets as shown in Fig. 4.8.

Hence, B-rep schemes are considered to be very useful, particularly when used to construct solid models of unusual

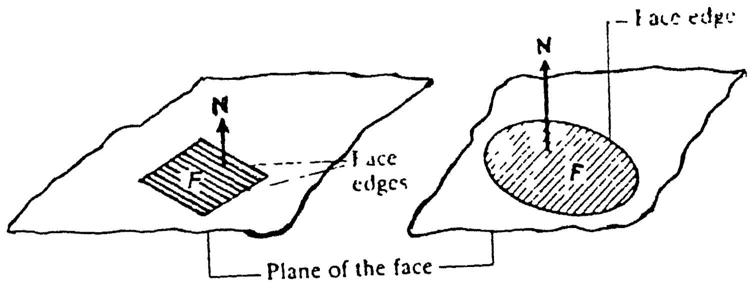


(a) Same geometry but different topology

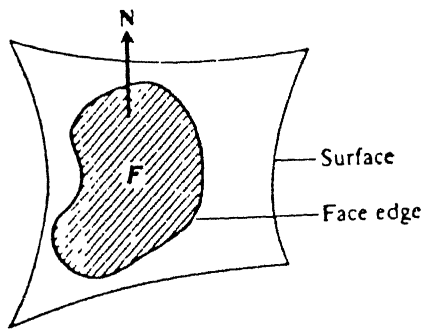


(b) Same topology but different geometry

Fig 4.5 Difference between geometry and topology of an object

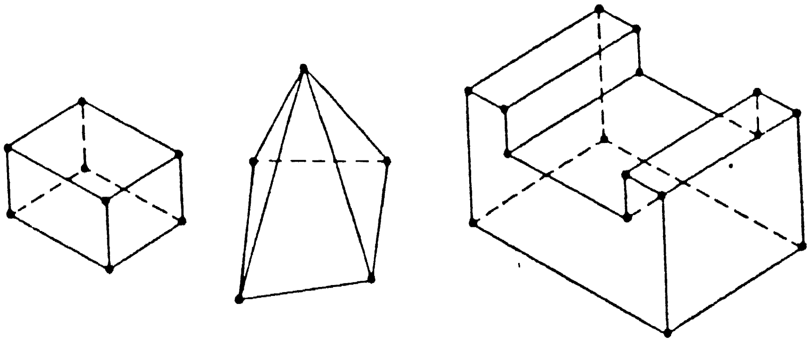


(a) Underlying surface is a plane

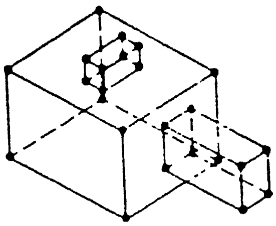


(b) A general underlying surface

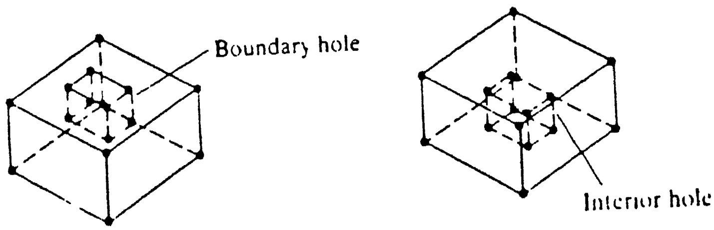
Fig 4.6 Underlying surface of a face



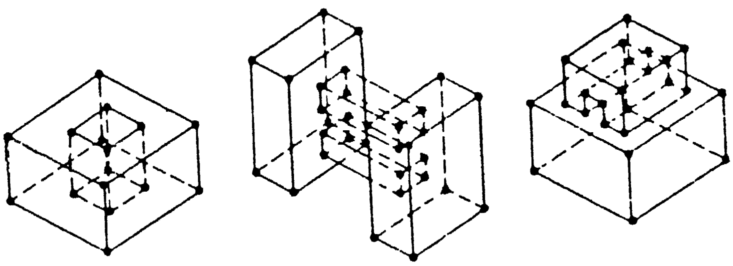
(a) Simple polyhedra



(b) Polyhedra with faces of inner loops



(c) Polyhedra with not through holes



(d) Polyhedra with handles (through holes)

Fig 4.7 Types of polyhedral objects [Zeid (1991)]

Table 4.1 Counts of Polyhedral Values for Objects of Fig 4.7 [Zeid (1991)]

Object number	F	E	V	L	B	G
1	6	12	8	0	1	0
2	5	8	5	0	1	0
3	10	24	16	0	1	0
4	16	36	24	2	1	0
5	11	24	16	1	1	0
6	12	24	16	0	2	0
7	10	24	16	2	1	1
8	20	48	32	4	1	1
9	14	36	24	2	1	1

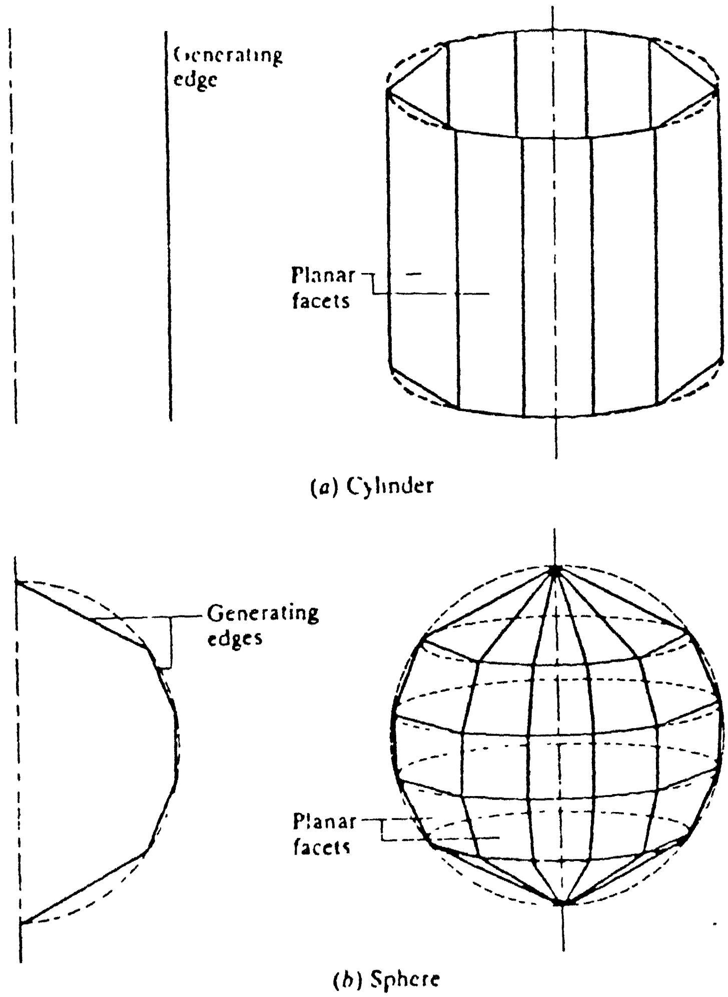


Fig 4.8 Faceted B-rep of a cylinder and a sphere

shapes. Also algorithms based on B-rep are reliable and competitive than those based on CSG, although it requires large amounts of storage. Conversion from CSG to B-rep is possible, however, converting B-rep to CSG is not well known.

4.7.3 PROCESSING MODULES

The functions of different computational modules in the fixture design system can be classified into eight main parts. These modules use both symbolic and analytic methods, as required. A brief description of these modules is as follows:

1. **Selection of Primary Locating Surface**

Based on the technical and geometric information about the workpiece, as it is retrieved from the product model, this geometric reasoning module selects the primary locating surfaces. This module taken into account the gravity force direction. Prime consideration is the stability of the workpiece as it is placed on three pins.

2. **Selection of Secondary Locating Surface**

Similarly based on the information gathered from product model and process plan module i.e. direction of primary cutting force, the plane containing two pin locators i.e. secondary locating plane is selected.

3. **Selection of Tertiary Locating Surface**

Again based on part geometry and the direction of primary cutting force, the plane containing one pin locator is selected, based on geometric reasoning.

4. **Selection of Clamping Surfaces**

Based on geometric information provided by the product module, technical information provided by the process plan module and information about previously selected three locating surfaces, the primary clamping surfaces, secondary clamping surfaces and the tertiary clamping surfaces are selected, opposite to primary, secondary and tertiary locating surfaces.

5. **Selection of Primary Locating Position**

On primary locating surface and optimizing the stability of the workpiece, the coordinates of actual position of three locators are calculated.

6. **Selection of Secondary and Tertiary Locating Positions**

On secondary locating plane, coordinates of actual position of two locators and on tertiary locating surface, coordinate of single locator are calculated, taking care that they do not interfere with cutting path envelope.

7. **Selection of Clamping Positions**

This module finalizes the position of horizontal and vertical clamps on the appropriate surfaces of the workpiece.

8. **Selection of Fixture Components**

This module selects suitable fixture locators (rest button types) based on compliance analysis of the locators. The operation plan module comes into picture to help calculating deflection and size of locators to resist the deflection. It, finally, establishes a stable fixture configuration.

4.7.4 OUTPUT MODULE

The output module lists all the clamping, supporting and locating faces and the positions of the exact clamping, supporting and locating points. This module also lists the modular elements to be used in building the fixture.

4.8 MODULAR FIXTURE COMPONENTS

The modular fixturing elements may be organized into 3 categories namely Base plates, Locators and Clamps [Ngoi and Leow (1994)].

4.8.1 BASE PLATES

The base plate (Fig. 4.2) is a plate which provides an accurate mounting surface for the complete fixture. In this work, the base plate considered has numerous grid holes in which the locators, supports and the clamping system sit on. The selection of base plate depends on

- overall size of the workpiece
- shape of the workpiece
- machine's pallet size
- the machining process
- type of machining centre used - vertical or horizontal.

The secondary and tertiary locators, which are to be placed along X and Y axes, are screwed to grid holes based plate called angle plate. This angle plate is fixed to the base plate to prevent its lateral movement.

4.8.2 LOCATORS

The locating elements can be rest buttons, screw jacks with tips of various shapes, support cylinders, edge blocks, edge bars, locating pin, V blocks and floating ball support [Boyes (1982)]. But in this work, locators of the type rest buttons, V blocks and floating ball support are considered only.

4.8.3 CLAMPS

In the present work, clamps are categorized into side clamps and top clamps. The top clamps work by pressing the workpiece against the base plate from the top. Side clamps press the workpiece from the sides. When shape of the workpiece is peculiar and no standard clamp is able to clamp it down to the baseplate and/or angle plate, self-assembled clamps can also be used.

CHAPTER 5

COMPLIANCE ANALYSIS IN FIXTURE DESIGN

The most common method of evaluating the strength of any element is the comparison of the stresses developed in it under the given load with the safe allowable stresses. The strength condition is thus written as:

$$\sigma \leq \sigma_{per}$$

$$\tau \leq \tau_{per}$$

where $\sigma_{per} = \sigma_{lim}/n$ (5.1)

and $\tau_{per} = \tau_{lim}/n$

In the above equations, σ and τ are the tensile and shear stresses developed in the element, σ_{per} and τ_{per} are the safe permissible stresses, and the σ_{lim} and τ_{lim} are limiting normal stress and limiting shear stress respectively and n is the factor of safety [Ryder (1969)].

5.1 BASIC PRINCIPLES OF DESIGN FOR RIGIDITY

The operating properties of fixtures are often determined by the degree of rigidity of their individual elements, mainly locators and supports, as they are the ones which resist applied forces and weight of the workpiece. The rigidity of a fixture element is defined by the degree of deformation undergone by an element for an external load. The behaviour of an individual

element under static loading can be examined from the force-displacement relationship.

If, dp if the change in force and ds is the change in displacement, then K is the degree of rigidity or static stiffness of the element, and given as

$$K = \frac{dp}{ds}$$

This relation is valid even if non linear relationship exist between force and displacement.

If the relationship between force and displacement is linear [$P = f(\delta)$] in the whole range of variation of force, as is generally the case under elastic loading, then the static stiffness K is expressed as

$$K = \frac{P}{\delta} \qquad (5.2)$$

Where P = force,

δ = displacement

Hence $$K = \frac{AE}{L} \qquad (5.3)$$

Where A = area of cross section of elements,

E = Modulus of elasticity of element material,

L = Original length of the element.

For two elements of equal stiffness,

$$\frac{E_1 A_1}{L_1} = \frac{E_2 A_2}{L_2}$$

if the elements are of equal length, i.e. $L_1 = L_2 = L$ but different material, then

$$E_1 A_1 = E_2 A_2$$

The weights of the elements will be $\gamma_1 A_1 L$ and $\gamma_2 A_2 L$ where γ_1 and γ_2 are specific weights of elements 1 and 2 respectively The ratio of the weights will be

$$\frac{W_1}{W_2} = \frac{\gamma_1 A_1}{\gamma_2 A_2} = \frac{E_2 \gamma_1}{E_1 \gamma_2} = \frac{E_2 / \gamma_2}{E_1 / \gamma_1} \qquad (5.4)$$

This ratio $[E/\gamma]$ which characterizes the quality of the material for elements which should satisfy the requirements of rigidity is called '**unit rigidity**'.

The larger the unit stiffness of a material, the smaller is the weight of the element required to ensure that the deflection of the element due to a particular load doesnot exceed a specified value [Sen and Bhattacharyya (1975)].

The unit stiffness values of some common engineering materials are given in Table 5.1 [MH (1985)].

Table 5.1: Unit Rigidity in Tension for Some Engineering Materials

Material	E Kgf/cm^2	γ Kgf/cm^2	E/γ
Low Carbon Steel	2.0×10^6	7.8×10^{-3}	2.56×10^8
Medium Carbon Steel	2.1×10^6	7.8×10^{-3}	2.69×10^8
Alloyed Steel	2.1×10^6	7.8×10^{-3}	2.69×10^8
Grey Cast Iron	1.2×10^6	7.2×10^{-3}	1.66×10^8
Duraluminium	0.75×10^6	2.8×10^{-3}	2.68×10^8

In this work these comparative values of different materials for design for rigidity, are used to choose common structural steel as the material for the locators and supports used in the fixture design.

Often, it is considered more convenient to use the term '**compliance**' which is inverse of stiffness or degree of rigidity for analyzing the behaviour of elements under static loading.

Compliance, $C = (1/K)$ (5.5)

Similarly for stiffness in torsion of an element loaded by twisting moment, M_m is given by:

$$K_T = \frac{M_m}{\phi} = \frac{GJ}{L} \quad (5.6)$$

Where ϕ = Angular deformation or twist,

G = Modulus of rigidity of element material,

J = Polar moment of inertia of the element.

For structural steel elements, permissible value of δ/l is ·25 percent and permissible value of ϕ is 0.5 degrees per metre length, for normal accuracy [MH (1985)].

5.2 DESIGN OF LOCATORS

For simplicity of computation and with the understanding that no appreciable loss of accuracy will be encountered, it can be safely assumed that no cross compliance comes into the picture. In other words, primary locators are designed on the basis of

vertical forces (which include weight of the workpiece also) and twisting moment about vertical or Z axis only Similarly secondary locators are designed on the basis of horizontal primary cutting force(s) and twisting moment(s) about the respective axis only. Tertiary locators, for simplicity, are taken as same as secondary locators.

As described, previously, in chapter 4, the locators are cylindrical in shape (rest buttons) with relatively very small height and comparatively large diameter. A further increase in the diameter of rest buttons and/or further reduction in height lead it to infinite rigidness. In the present work, height of the locator is kept to a bare minimum possible value and then its minimum diameter, is calculated based on compliance analysis so that induced stresses are within the permissible values.

Let nth locator be acted upon by a force P_n and a twisting moment M_{mn}, which can be calculated by knowing the cutting forces, cutting torque, weight, surface areas of material cut from locator surfaces, and center of gravity. Then with the help of equation (5.2) and equation (5.3), the diameter d of the locator is calculated as

$$d_f = \left(\frac{4 \ P_n L}{\pi \ E \ \delta_{per}} \right)^{1/2} \tag{5.7}$$

and with help of equation (5.6), d is calculated as

$$d_m = \left(\frac{32 \ M_{mn} \ L}{\pi \ G\phi_{per}} \right)^{1/4} \tag{5.8}$$

where δ_{per} and ϕ_{per} are the permissible values of elongation/compression and the angular twist respectively.

Of the two values of 'd' calculated as by equations (5.7) and (5.8), whichever value of d is larger, that is taken as minimum possible value of the diameter of the locator.

5.3 ESTIMATE OF CUTTING WRENCHES

In this section, widely used methods to estimate the cutting wrenches are presented. Here the word cutting wrench is used instead of cutting force since cutting can generate both force and torque.

The physical phenomena of cutting is considered to be so complicated and so many elements are involved that even for a single tip cutting it is almost impossible to estimate the cutting wrench accurately. It may be mention that estimates of cutting wrenches for multipoint cutters e.g. drilling, milling etc, where much more complex cutters than a single tip cutters are used, are always approximate. There are a few well known formulae for estimating cutting wrenches as taken from [MTDH (1982)] [PT (1980)] and [TMEH (1983)].

5.3.1 CUTTING WRENCH IN MILLING

In milling, the cutting force tangent to the effective cutting radius of the cutter is dominant and can be given as

follows:

Diameter of the cutter = D (mm)

Revolutions per minute = n (rpm)

Cutting speed per minute, $V = \frac{\pi Dn}{1000}$ (m/min)

Feed per minute = S_m (mm/min)

Depth of cut = t (mm)

Width of cut = b (mm)

Then

$$\text{Metal removal rate, } Q = \frac{b.t.S_m}{1000} \quad (cm^3/min) \tag{5.9}$$

$$\text{and Power at the spindle } N = (U.K_h.K_r)\ Q \text{ (KW)} \tag{5.10}$$

Where

U = Unit power (KW /cm^3/min) (Table 5.2)

K_h = Correction factor for flank wear (Table 5.3)

K_r = Correction factor for radial rake angle (Table 5.4)

[MTDH(1982)].

From these tables, the maximum value of the product $(U.K_h.K_r)$ can be taken as 0.5138 for maximum safety.

$$\therefore N = 0.5138\ Q \tag{5.11}$$

Tangential cutting force, $P = 6120 \frac{N}{V}$ Kgf

$$\text{or} \quad P = 6120 \times 0.5138 \times \frac{Q}{V} \tag{5.12}$$

$$\text{or} \quad P = \frac{3.1445\ b.t.S_m}{V} \tag{5.13}$$

Table 5.2 Average Unit power U, for milling [MTDH (1982)]

Work material	Tensile strength kgf/mm^2 Hardness HB	Unit power U. $kW/cm^3/min$ *								
		Average chip thickness, mm.								
		0.025	0.05	0.075	0.1	0.15	0.2	0.3	0.5	0.8
Free machining	40	54	45	41	39	35	33	30	26	23
steels	50	60	50	45	42	39	36	32	29	26
Mild steels	60	66	55	50	47	42	39	35	31	28
Medium carbon	70	69	59	53	50	45	42	37	33	30
steels	80	73	63	56	52	48	44	40	35	32
Alloy steels	90	78	65	59	56	50	47	42	38	34
Tool steels	100	80	69	62	59	53	49	44	39	35
	110	85	72	65	61	56	53	51	44	36
Stainless steels **	150	80	71	66	61	57	52	48	44	40
	160	86	76	72	67	62	58	54	50	46
	170	92	82	78	73	68	61	56	52	48
	180	99	90	84	80	75	69	62	59	52
	190	104	96	91	86	81	78	69	64	58
	200	110	101	96	91	88	85	78	71	60
Cast iron: ** Grey, Ductile, Malleable	160	30	26	24	22	21	19	18	16	14
	170	31	28	25	24	22	20	19	17	15
	180	35	30	27	25	23	22	21	19	17
	190	36	31	29	27	24	23	21	20	17
	200	38	33	30	28	26	24	22	20	18
	220	42	36	33	31	29	26	24	22	20
	240	46	40	36	34	31	29	27	24	21
	260	50	43	39	37	33	31	29	26	23
	280	53	46	42	39	36	34	31	28	25
Aluminium alloys	10	13	11	9	9	8	7	6	6	5
	20	19	16	14	13	12	11	10	8	7
	30	24	20	17	16	14	13	12	10	9
	40	28	23	21	19	17	16	14	12	11
	50	32	26	23	22	19	18	16	14	12
Copper alloys	–	25	21	19	17	16	15	13	12	10
Magnesium alloys	10	9	7	6	6	5	5	4	4	3
	15	10	9	8	7	6	6	6	5	4
	20	12	10	9	8	7	7	6	5	4
	25	13	11	10	9	8	7	7	6	5
Titanium alloys: *Ti Al Cr*	110	59	51	47	45	41	39	36	32	30
Titanium alloys: Pure *Ti*	–	61	52	48	45	41	38	35	31	28
Titanium alloys: *Ti Al Mn*	–	67	58	53	50	45	43	39	35	31
Titanium alloys: *Ti Al V*	–	68	59	54	52	47	45	41	37	34
Titanium alloys: *Ti Al Cr Mo*	–	77	66	60	57	52	49	45	40	36

* Multiply the table values by 10^{-3} ** Values in HB

Table 5.3 Correction factor for flank wear [MTDH (1982)]

Flank wear	Average chip thickness	Correction coefficient, K_h									
		Hardness of work material									
		HB							HRC		
mm	mm	125	150	200	250	300	350	400	51	56	61
0.2	0.1	1.16	1.17	1.18	1.19	1.2	1 21	1 22	1.25	1.33	1.38
	0.3	1.06	1.07	1.08	1.08	1.09	1.09	1.09	1.13	1 16	1.18
	0.5	1.04	1.05	1.05	1.05	1.05	1.06	1.07	1.08	1.12	1.13
	1	1.02	1.02	1.03	1.03	1.03	1.03	1.03	1.04	1.06	1.07
0.4	0.1	1.5	1.5	1.5	1.53	1.57	1.67	1.78	1.8	1.92	2.12
	0.3	1.2	1.2	1.2	1.22	1.23	1.27	1.32	1.36	1.41	1.52
	0.5	1.12	1.12	1.14	1.15	1.16	1.19	1.24	1.26	1.3	1.38
	1	1.06	1.06	1.07	1.07	1.08	1.1	1.12	1.14	1.16	1.2
0.6	0.1	1.68	1.71	1.73	1.84	1.94	2.09	2.2	2.43	2.72	2.82
	0.3	1.26	1.25	1.29	1.33	1.37	1.44	1.5	1.61	1.78	1.85
	0.5	1.17	1.19	1.2	1.23	1.26	1.3	1.37	1.47	1.57	1.61
	1	1.09	1.1	1.1	1.12	1.14	1.16	1.19	1.25	1.3	1.33
0.8	0.1	1.91	2.04	2.1	2.34	2.47	2.54	2.65	2.99	3.26	–
	0.3	1.35	1.41	1.42	1.52	1.56	1.62	1.7	1.9	2.02	–
	0.5	1.23	1.28	1.32	1.36	1.38	1.43	1.52	1.66	1.74	–
	1.0	1.12	1.14	1.15	1.17	1.18	1 23	1.27	1.35	1.4	–
1	0.1	2.18	2 32	2.39	2.54	2.65	2.84	3.15	3.46	–	–
	0.3	1.45	1.5	1.56	1.67	1.7	1.74	1.9	2.16	–	–
	0.5	1.3	1.34	1.39	1.47	1.45	1.51	1.67	1.84	–	–
	1	1.15	1.16	1.17	1.2	1.23	1.27	1.35	1.44	–	–

Table 5.4 Correction factor for rake angle [MTDH (1982)]

Rake angle, γ *degrees*	–15	–10	–5	0	+5	+10	+15	+20
Correction coefficient, K_γ	1.35	1.29	1.21	1.13	1.07	1	0.93	0.87

5.3.2 CUTTING WRENCH IN DRILLING

In drilling, cutting wrench is divided into drill torque and downward thrust. Reasonable estimates of torque and thrust, can be made from the following formulae:

Let

Diameter of Drill = D (mm)

Revolutions per minute = n (rpm)

Cutting speed, $V = \frac{\pi D n}{1000}$ (m/min)

Feed per revolution, = S (mm/rev)

Power at the spindle, $N = 1.25\ D^2 K n\ (0.056+1.5S)/10^5$ (KW)

(5.14)

Where

K = Material factor (Table 5.5) [MTDH (1982)].

Maximum value of K, from Table = 2.41

Hence

Cutting Torque, $M_m = 975\ N/n$, Kgf.m (5.15)

and

Cutting Thrust, $P = 1.16\ KD\ (100\ S)^{0.85}$ (5.16)

5.3.3 CUTTING WRENCHES IN TAPPING

In tapping, cutting wrench is in the form of cutting torque only, which can be calculated as [MTDH (1982)].

Let

Diameter of tap i.e. nominal diameter of threads = D (mm)

Table 5.5 Materials factors K, for Drilling and Reaming [MTDH (1982)]

Work Material	Hardress *HB*	UTS kgf/mm^2	Material factor K
Free-machining steels	167	59 9	1.03
	183	63	1.42
Mild steels	121	44.1	1 07
	160	56.7	1.22
Medium carbon steels	152	55.1	1.15
	197	67.7	1.45
Alloy steels Tool steels	163	58 3	1.56
	174	61.4	2.02
	229	78.8	2.1
	241	81.9	2.32
Stainless steels	187	64.6	1.56
	269	92.6	2.41
Cast iron: Grey, Ductile, Malleable	177	21.3	1
	198	28.4	1.5
	224	35.1	2.03
Aluminium alloys	–	–	0 55
Copper alloys	–	–	0.55
Magnesium alloys	–	–	0.45

Revolutions per minute = n (rpm)

Thread pitch = P (mm)

Material factor = K (Table 5.5) [MTDH (1982)].

Power at the spindle = $N = 0.433\ DP^2\ nK/10^4$ (KW)

(assuming maximum i.e. 90% thread engagement)

Cutting Torque, $M_m = 975\ N/n$ (5.17)

This section helps in guiding the system to perform the force analysis and design the specific locators and supports.

CHAPTER 6

SYSTEM DESIGN AND IMPLEMENTATION

Some parts of the methods described in previous chapter are implemented using Turbo/C 2.0 in DOS 5.0 environment on a PC-386. The procedures are written in C, as it is considered to be a powerful language. The parts of the system actually implemented and tested are: (i) geometrical positioning of locators, clamps and supports and (ii) the choice of these elements based on force analysis. The system, developed as a module of an over all CAPP package, is automated in this sense that the user inputs the part geometry and process plan and there is no further user interaction necessary. The system outputs the fixture configuration in terms of coordinates of locators, supports and clamps and their size and type.

The following sections outlines the algorithms used in achieving the objective.

6.1 CALCULATION OF UNIT INNER NORMALS

The synthesis of the fixturing positions begins with the information retrieved from the 'informationally complete' product model. After reading in, the B-rep of the workpiece geometry, unit inner normals of each and every surface are find out and

stored. For it, the right hand principle is used as well as the convention that if outer normal of the surface points in positive Z direction, and one traverse the boundary of the surface, the surface/object is always towards the left hand side of the direction of movement, is taken care of. The normal is calculated for the plane with the help of coordinates of three vertices lying on the plane.

6.2 SELECTION OF PRIMARY LOCATING SURFACE

Primary locating surface is the surface which is used to support the workpiece against its weight. On this surface, position of three locators is chosen. Selection of primary locating surface is done with the help of direction of force due to gravity (0,0,-1), which may be altered if the base plate is not to be placed in XY plane. A simple rule is

IF

the surface S_n (the nth surface of the workpiece) is a possible primary locating surface against the direction of force due to gravity $\hat{fg}$

THEN

$$- 1.0 \leq \hat{n} . \hat{fg} < 0.0 \qquad (6.1)$$

where

$\hat{n}$ = unit inner normal of surface S_n

$\hat{fg}$ = direction cosine of the force due to gravity

However, equation (6.1) may lead to impractical solutions. It may lead to surfaces with high slopes, as angle can vary from 180^{o} to almost 90^{o}. However, projection of such surfaces on a plane perpendicular to the force due to gravity is minimal. It can hardly provide any supporting area and the contact between a locator and the workpiece on such surfaces will not be stable. We therefore modify the above rule as follows:

IF

the surface, S_n is a possible primary locating surface against the force due to gravity.

THEN

$$- 1.0 \leq \hat{n}.\ \hat{fg} < - 0.8 \qquad (6.2)$$

There may be one or more than one such surfaces. These surfaces should be further checked that whether they are flat and machined surfaces or cast or curved surfaces. If there are more than one such surfaces, and they donot lie on the same XY plane, then that particular area of the surfaces, which lie above the base/bottom most primary locating surface is not considered for locating purpose.

6.3 SELECTION OF SECONDARY AND TERTIARY LOCATING SURFACES

The two-point secondary locating surface should be

1. Perpendicular to the primary supporting surface(s)
2. Perpendicular to the major cutting force direction.

The one-point tertiary locating surface

1. Should be perpendicular to the primary supporting surface(s)
2. Should not be parallel to secondary locating surface(s)

It should be noted that the most satisfactory locating surfaces are those which are in mutually perpendicular planes.

The rule for locating the secondary locating surface is similar to above mentioned rule (6.2) i.e.

IF

the surface, S_n is a possible secondary locating surface against the primary cutting force, $\mathbf{F}_{major}$

THEN

$$-1.0 \leq \hat{n} \; \hat{f}_{major} < -0.75 \tag{6.3}$$

where $\hat{f}_{major}$ is the direction cosine of major/primary cutting force direction.

If the primary cutting force direction is in between 41.41° and 48.59°, then of the two XZ and YZ planes, whichever is bigger is chosen as secondary locating surface.

Based on the aforesaid conditions and the list of secondary surfaces, tertiary locating surfaces are selected.

Similar to the primary locating surfaces, if more than one secondary locating surfaces exist, then in between secondary and tertiary locating surfaces are suitable modified.

It is also checked that the surfaces selected are not to be machined. With the help of configuration space approach i.e. knowing the cutting tool path envelope, if any of the selected surface is to be machined, it is eliminated from the list.

6.4 SELECTION OF CLAMPING SURFACES

The general rule for selecting the clamping surfaces is

IF

- the D_n of the surface S_n should satisfy the constraint

$$0.8 < D_n \leq 1.0$$

- the surface is not to be machined
- the surface area is large enough for clamping

THEN

Select the surface as a possible clamping surface.

Here, D_n can be vector dot product of unit inner normal $\hat{n}$ and direction of force due to gravity for vertical clamping and vector dot product of unit inner normal $\hat{n}$ and direction of primary cutting force $\hat{f}_{major}$ for secondary clamping.

The selected clamping surfaces has to be opposite their respective locating surfaces.

The tertiary clamping surface has to be non parallel, preferably perpendicular, to the secondary clamping surface.

The knowledge about the type of surface is also properly taken care of. If the clamping face happens to be non-planar, multiple clamps at different positions on the face may be required to ensure stability of the workpiece.

6.5 SELECTION OF PRIMARY LOCATING POSITIONS

The search for coordinates of the actual position of primary locators (three points) starts with listing all probable points P_{loc} on the grid plate. At fixed distance R, equal to the distance between grid holes of the base plate selected, along the boundary of the primary locating surface(s) and at a distance R/2 inside the bounded area of primary locating surface(s), P_{loc} are determined.

Points of P_{loc} are used as vertices to form all possible triangles. All such triangles are eliminated that do not enclose the projection of the centre of mass (COM) of the object within the projected triangular region (projected on the base plate) formed by the three points locators. This is done by point membership classification (PMC) [Preparata and Shamos (1985)].

Among the remaining triangles whose minimum perpendicular distance from the COM (of the three edges) is maximum is selected, to minimize toppling effect. The vertices of such triangle are actually the position of 3 pins or primary locators.

If more than one, such triangle exist, then that triangle is chosen whose area is maximum. Thus X and Y coordinates of all three locators are provided and Z coordinate is found from the respective coordinates of the primary locating surface(s) in which these vertices lie.

If the surface chosen is flat and machined then rest button are chosen as locators, else if the surface is curved, V block are

chosen, else if the surface is non uniform curved or casted or forged, floating ball supports are chosen. Same case applies for secondary and tertiary locators also.

6.6 SELECTION OF SECONDARY AND TERTIARY LOCATING POSITIONS

Secondary and tertiary locators lie either on X or Y plane. For secondary locators, based on the data retrieved from secondary locating surface(s), the minimum and maximum X (or Y) coordinates, depending on primary cutting force direction, are taken as position of two locators. The Y (or X) coordinates of the position of locators are the coordinates of secondary locating surface(s). The two locators should be placed as far apart as possible.

For tertiary locating position i.e. one point locator, the middle point of the distance machined, on the tertiary locating surface is taken as the Y (or X) coordinate of the locator. X (or Y) coordinate of the locator position is the coordinate of the tertiary locating surface itself.

For both secondary and tertiary locating positions, the Z distance is the maximum distance just below the minimum machined height (except for drilling). Z coordinate of all secondary and tertiary locators and clamps is taken as same.

6.7 SECTION OF CLAMPING POSITIONS

Clamping is used to restrict possible movements of a workpiece which cannot be arrested by the locators. It can be found in many machining operations, for instance, in a drilling operation when the drill cuts through the workpiece material an upward force may be created by interaction between the drill flutes and material remaining around the periphery of the drilled hole. To meet such conditions, the clamps are positioned at the most rigid portions of the workpiece. In most cases, it is preferable to position the clamps directly opposite to the supporting elements of the base plate.

Not going into the details of deformation of workpiece due to clamping force, it was found whether one clamp is needed for every locator or one clamp is sufficient for the entire clamping surface. This is done by comparing the thickness to length ratio against some predetermined factor, based on the material of workpiece. Here, thickness is the distance between locating and clamping surface and length is the lateral dimension for a projected 2 dimensional case. If the ratio is greater than or equal to the factor then choose one clamp per clamping surface else choose one clamp for each locator.

6.8 DESIGN OF LOCATORS

As discussed and described in chapter 5, the primary, secondary and tertiary locators are designed so that they can withstand the forces and the torques acted upon them without any appreciable deformation setting in. If this parameter is not properly attended then the shape of the workpiece cut will be distorted and will not be according to the prescribed specifications.

Thus, the above sections help in selecting the exact positions of locators, supports and clamps and their size and type. Properly fixing the locators, supports and clamps at these positions on the base plate and angle plate leads to an elementary modular fixture fulfilling most of the primary objectives

6.9 FLOW CHART

The entire procedure, use by the present work, can be shown with the help of a flow chart as shown in Fig. 6.1.

6.10 ILLUSTRATIONS

The algorithm was tested with the help of some test cases. The Example 1 is a pre-worked component. Fig. 6.2 shows the part geometry of the input/blank workpiece and Fig. 6.3 shows the part geometry of the finished workpiece. The input data for the

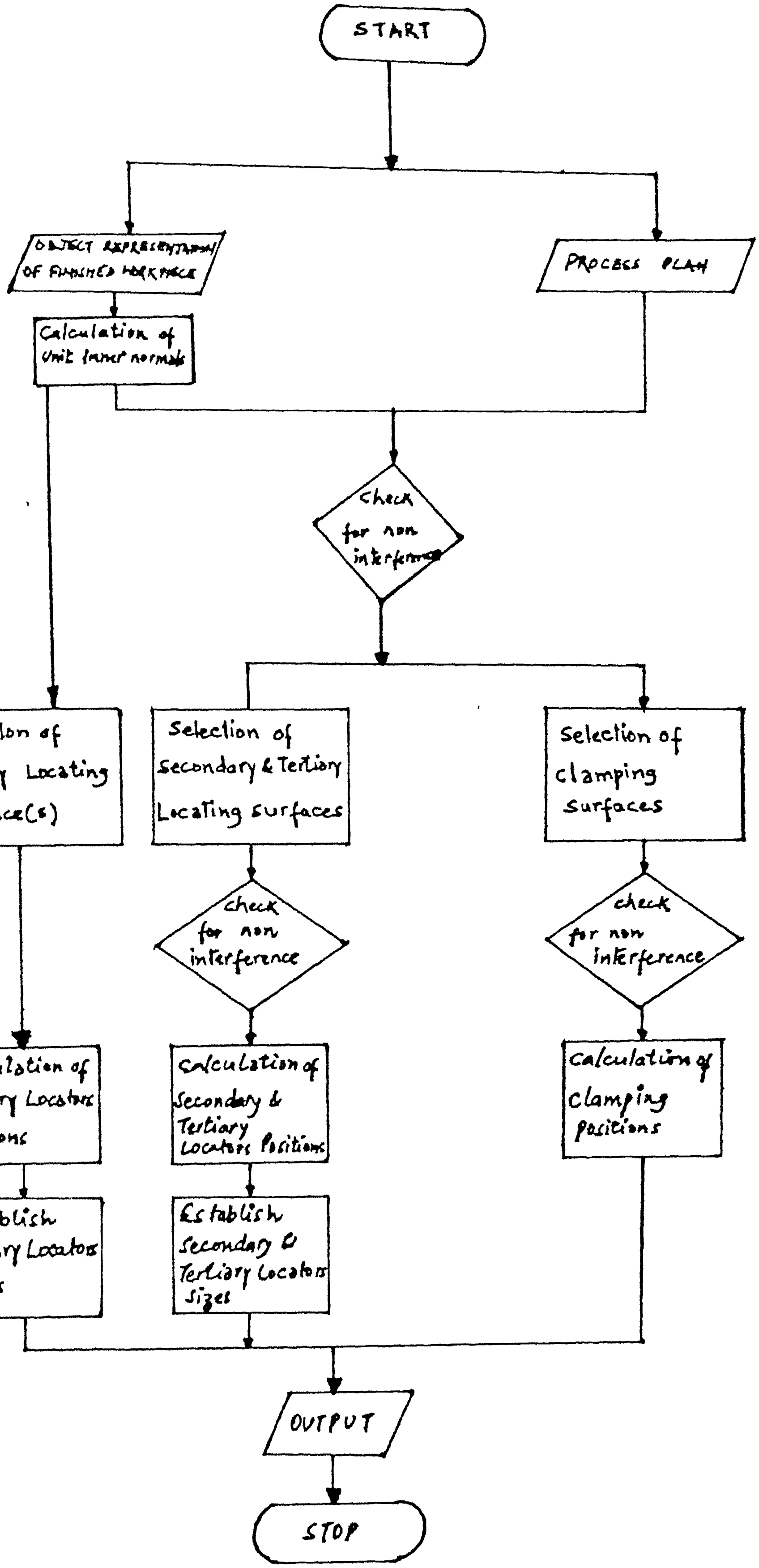


Fig 6.1 Flow Chart of the System

Example 1, required to run the program and produce results is shown in Table 6.1. With this input data, the results obtained were in the form of coordinates of actual position of locators & clamps and size of the elements used.

The system identifies surfaces 1,3 and 9 as primary locating surface; surface 22 as secondary locating surface and surface 19 as tertiary locating surface. It also identifies surface 8, 21 and 13 as primary, secondary and tertiary clamping surfaces respectively. Let L1, L2, L3 be positions of primary locators, L4, L5 be the position of secondary locators, and L6 be the position of tertiary locator. Similarly, let C1 be the position of primary clamp, C2, C3 be the position of secondary clamps and C4 be the position of tertiary clamp, then their coordinates of position are provided by the system, which happen to be:

L1 = (62.0, 98.0, 0.0)

L2 = (108.0, 98.0, 0.0)

L3 = (148.0, 52.0, 40.0)

L4 = (2.0, 100.0, 47.0)

L5 = (148.0, 100.0, 47.0)

L6 = (150.0, 50.0, 47.0)

C1 = (75.0, 50.0, 100.0)

C2 = (20.0, 0.0, 47.0)

C3 = (148.0, 0.0, 47.0)

C4 = (0.0, 50.0, 47.0)

Then with the help of force analysis (here, force due to milling operation in the direction 0, 1, 0), the size of all the locators is calculated and they cameout to be as cylindrical pieces of diameter 2.0 cm. and length 1.0 cm.respectively. As all the surfaces are flat in this case, so rest buttons are choosen as locators. By fixing the locators and the clamps at these positions on base plate and angle plates, a moduler fixture can be fabricated.

In a similar way, Examples 2,3 and 4 are shown in the figures 6.4 to 6.9 and the results are indicated there itself.

Thus, by analyzing the above examples, it can be said that the results appeared to be quite accurate.

All dimensions in cms.

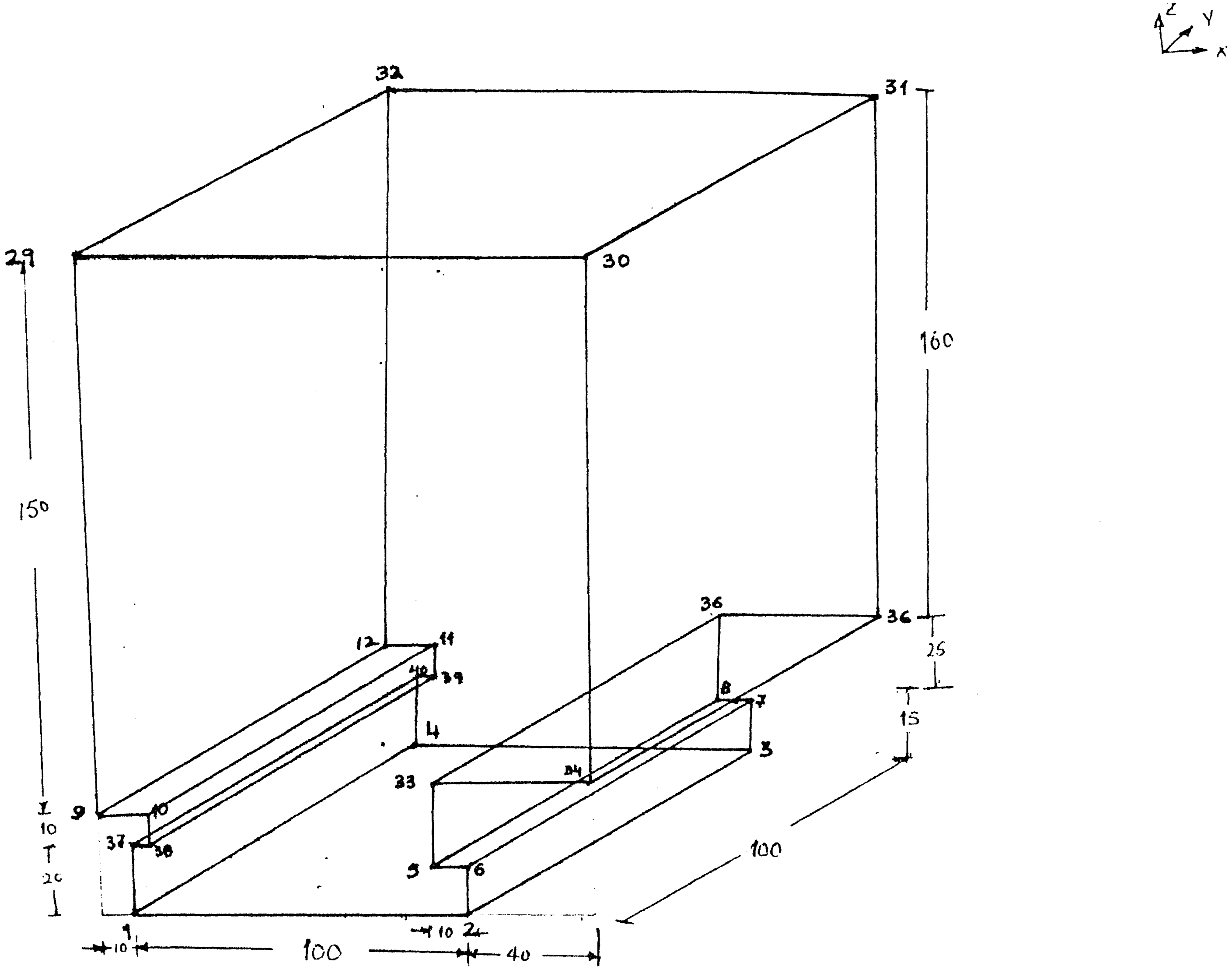


Fig 6.2 Input Part Geometry of Example 1

All dimensions in cms

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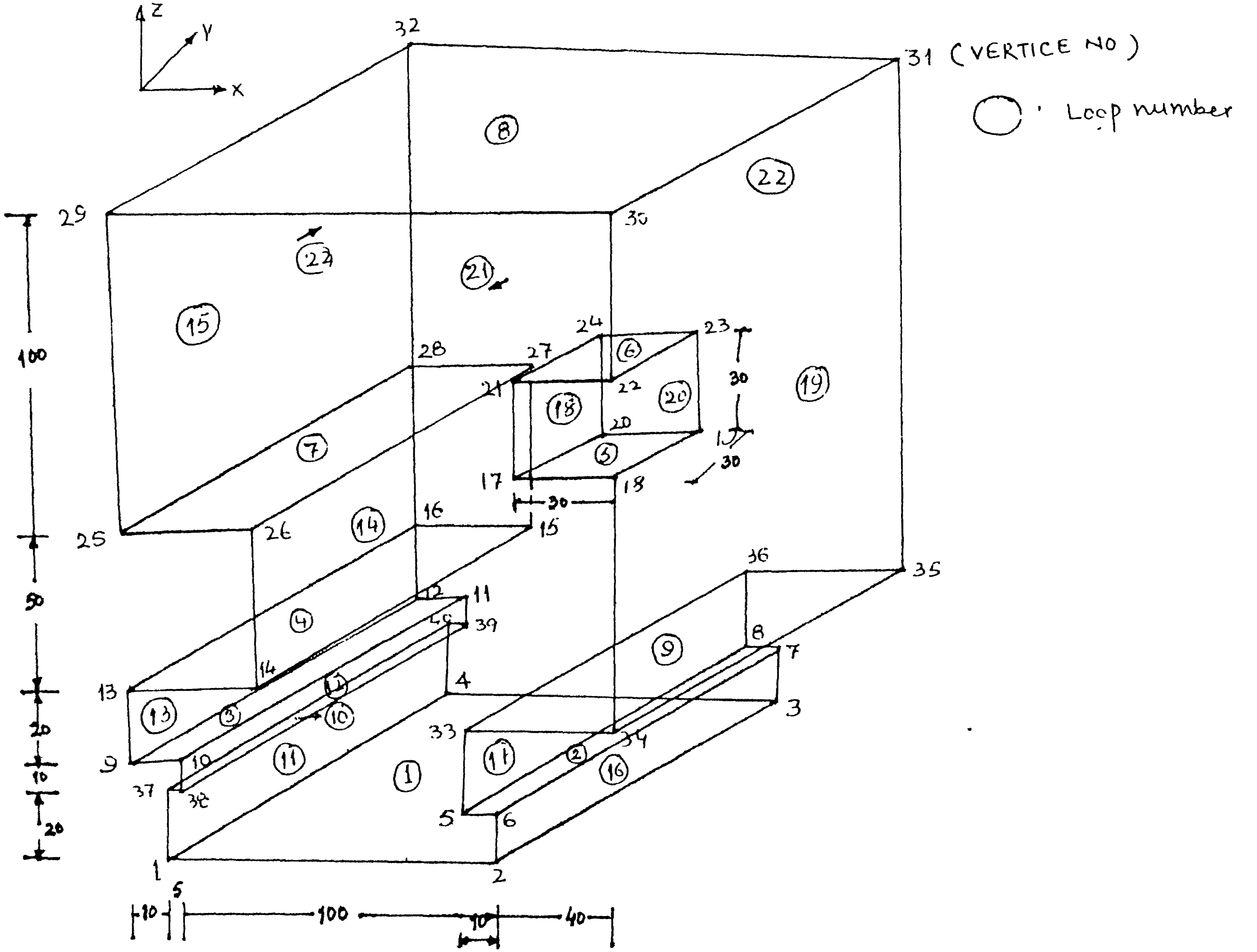


Fig 6.3 Finished Part Geometry of Example 1

Table 6.1: **INPUT DATA OF EXAMPLE 1**

INPUT DATA: PART_DRG.DAT

List of Vertices

No. of Vertices 40

Vertice No.	X	Y	Z	Coordinates
1	10	0	0	
2	110	0	0	
3	110	100	0	
4	10	100	0	
5	100	0	15	
6	110	0	15	
7	110	100	15	
8	100	100	15	
9	0	0	30	
10	15	0	30	
11	15	100	30	
12	0	100	30	
13	0	0	50	
14	40	0	50	
15	40	100	50	
16	0	100	50	
17	120	0	120	
18	150	0	120	
19	150	30	120	
20	120	30	120	
21	120	0	150	
22	150	0	150	
23	150	30	150	
24	120	30	150	
25	0	0	100	
26	40	0	100	
27	40	100	100	
28	0	100	100	
29	0	0	200	
30	150	0	200	
31	150	100	200	
32	0	100	200	
33	100	0	40	
34	150	0	40	
35	150	100	40	
36	100	100	40	
37	10	0	20	
38	15	0	20	
39	15	100	20	
40	10	100	20	

LIST OF EDGES

No of Edges 60

Edge No	Edge Type	Start Vert.	End Vert.
1	1	1	2
2	1	2	3
3	1	3	4
4	1	4	1
5	1	5	6
6	1	6	7
7	1	7	8
8	1	8	5
9	1	9	10
10	1	10	11
11	1	11	12
12	1	12	9
13	1	13	14
14	1	14	15
15	1	15	16
16	1	16	13
17	1	17	18
18	1	18	19
19	1	19	20
20	1	20	17
21	1	21	22
22	1	22	23
23	1	23	24
24	1	24	21
25	1	25	26
26	1	26	27
27	1	27	28
28	1	28	25
29	1	29	30
30	1	30	31
31	1	31	32
32	1	32	29
33	1	33	34
34	1	34	35
35	1	35	36
36	1	36	33
37	1	37	38
38	1	38	39
39	1	39	40
40	1	40	37
41	1	1	37
42	1	2	6
43	1	3	7

44	1	4	40
45	1	5	33
46	1	8	36
47	1	9	13
48	1	12	16
49	1	14	26
50	1	15	27
51	1	17	21
52	1	19	23
53	1	20	24
54	1	22	30
55	1	25	29
56	1	28	32
57	1	34	18
58	1	35	31
59	1	38	40
60	1	39	11

LIST OF LOOPS

No. of Loops 22

Loop No.	Loop Type	No. of Edges	Edges
1	1	4	4 3 2 1
2	1	4	5 6 7 8
3	1	4	12 11 10 9
4	1	4	13 14 15 16
5	1	4	17 18 19 20
6	1	4	24 23 22 21
7	1	4	28 27 26 25
8	1	4	29 30 31 32
9	1	4	36 35 34 33
10	1	4	37 38 39 40
11	1	4	41 40 44 4
12	1	4	59 10 60 38
13	1	4	47 16 48 12
14	1	4	49 26 50 14
15	1	4	55 32 56 28
16	1	4	2 43 6 42
17	1	4	8 46 36 45
18	1	4	20 53 24 51
19	1	8	34 58 30 54 22 52 18 57
20	1	4	19 52 23 53
21	1	20	1 42 5 45 33 57 17 51 21 54 29 55 25 49 13 47 9 59 37 41
22	1	16	3 44 39 60 11 48 15 50 27 56 31 58 35 46 7 43

LIST OF FACES

No. of Faces 21

Face No.	No. of Loops	Loops
1	1	1
2	1	2
3	1	3
4	1	4
5	1	5
6	1	6
7	1	7
8	1	8
9	1	9
10	1	10
11	1	11
12	1	12
13	2	13 15
14	1	14
15	1	16
16	1	17
17	1	18
18	1	19
19	1	20
20	1	21
21	1	22

X = 76.2923 Y = 50.1264 Z = 108.6435

$V = 3 \times 10^6$

PROC_PLAN.DAT

Primary Force Direction: 0 1 0

Primary Operation: Milling

Dia: 100

RPM: 5000

Feed: 1000

Depth of Cut: 50

Width of Cut: 50

Note: Edge type and loop type are based upon type of Edge and Loop i.e. 1 for planar, 2 for circular arc & 3 for curved.

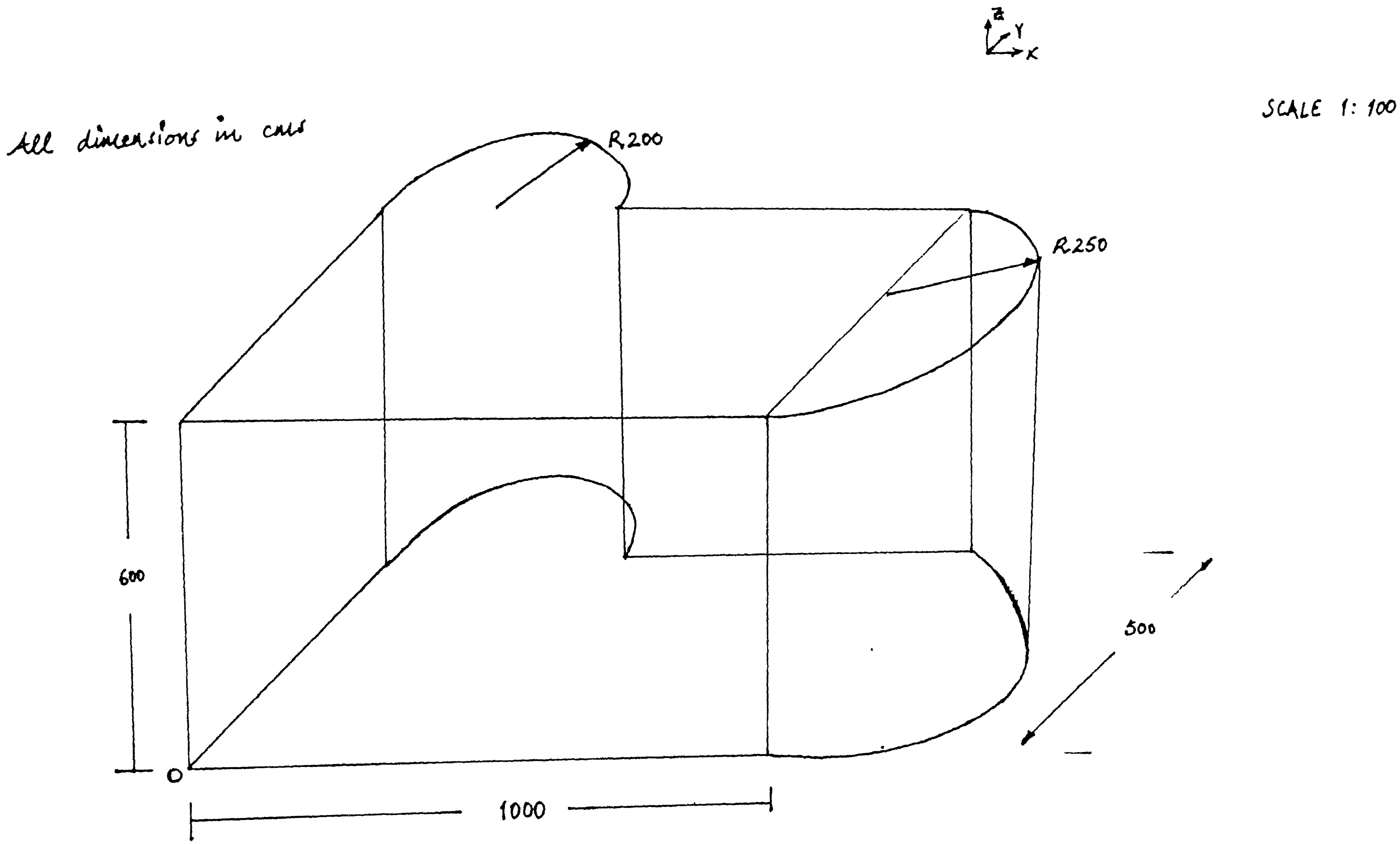


Fig 6.4 Input Part Geometry of Example 2

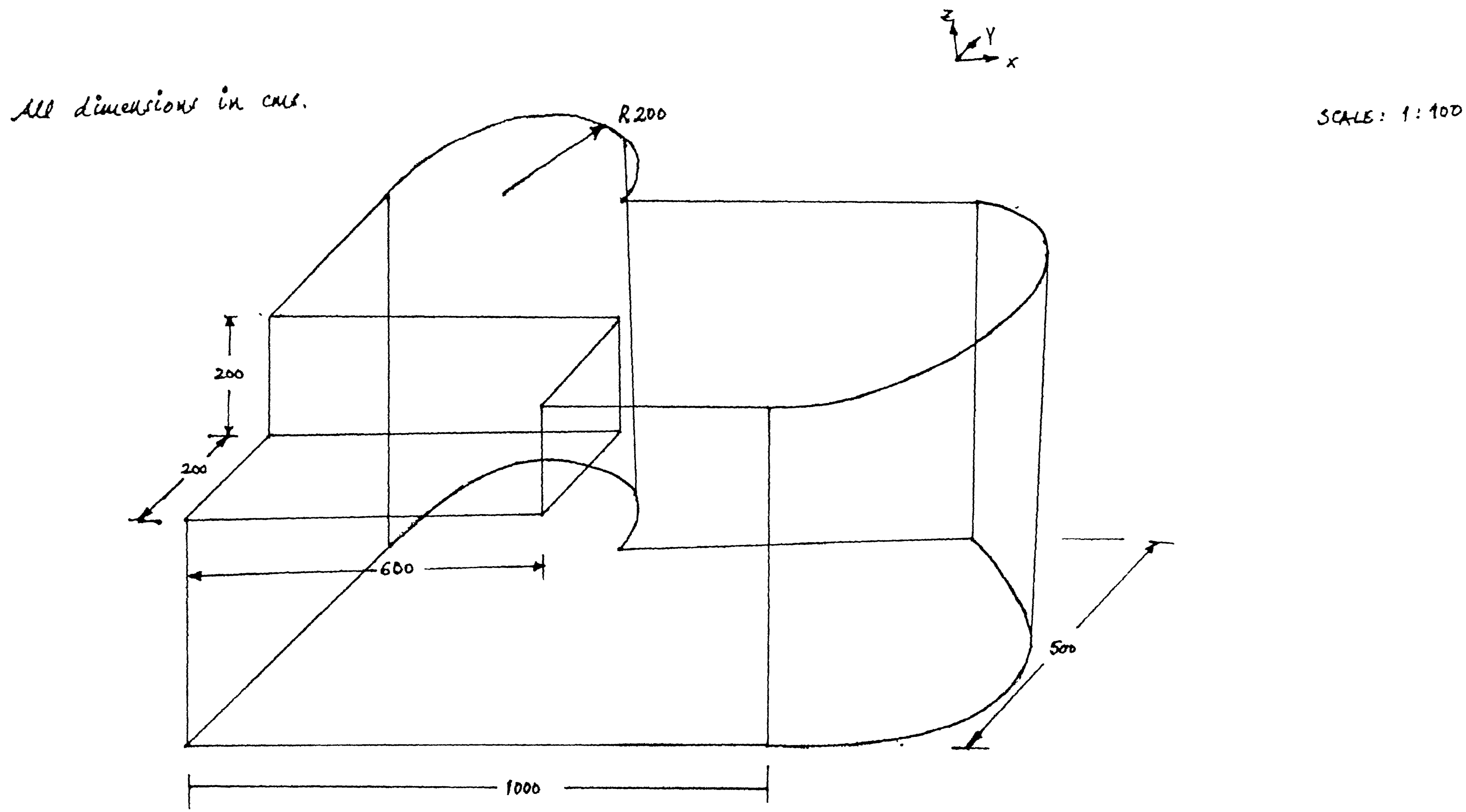


Fig 6.5 Finished Part Geometry of Example 2

RESULTS OF EXAMPLE 2.

LOCATORS	COORDINATES X	Y	Z
L1	31.289	533.355	0.000
L2	198.000	568.710	0.000
L3	998.000	2.000	0.000
L4	1161.613	75.223	397.000
L5	1161.613	568.710	397.000
L6	300.000	570.710	397.000
CLAMPS			
C1	500.000	250.000	600.000
C2	0.000	2.000	397.000
C3	0.000	568.710	397.000
C4	300.000	0.000	397.000

Dia of Primary Locators : 20 cm
Dia of Secondary / Tertiary Locators : 2 cm
L4, L5 & L6 will be V/Floating Ball Locators.

All dimensions in cms.

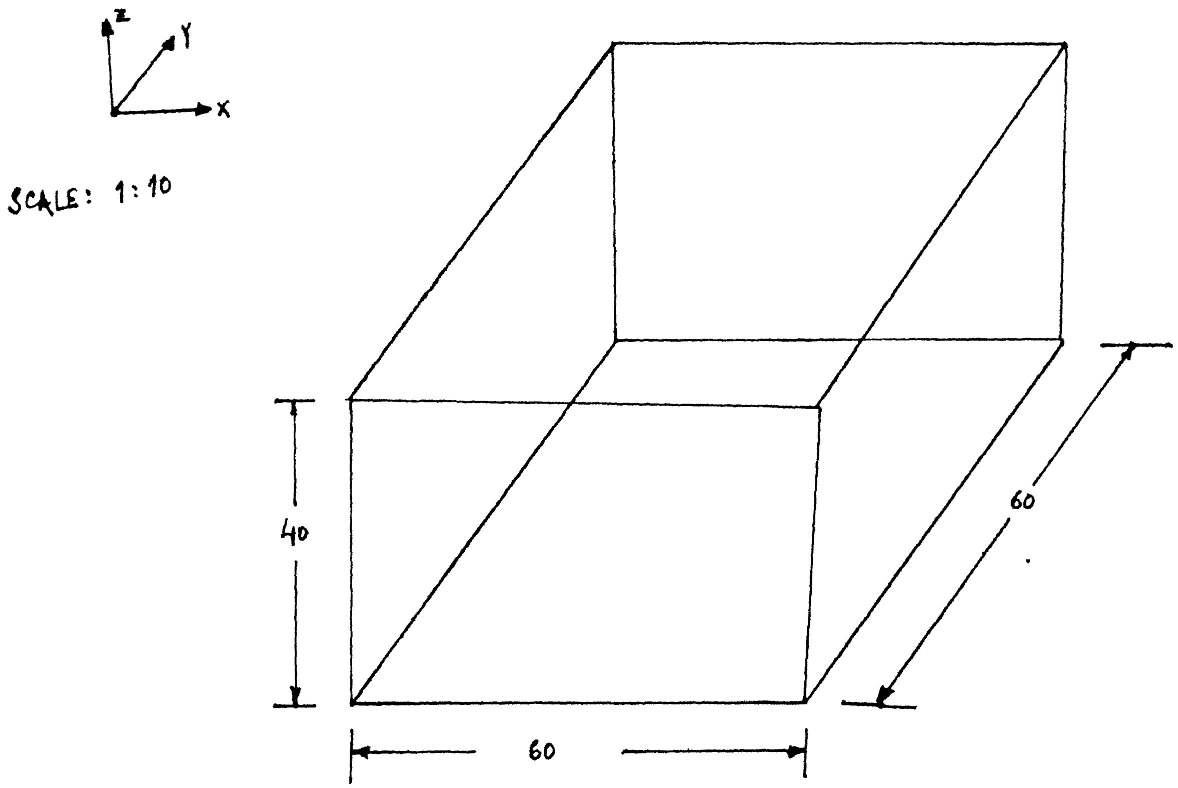
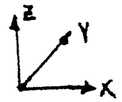
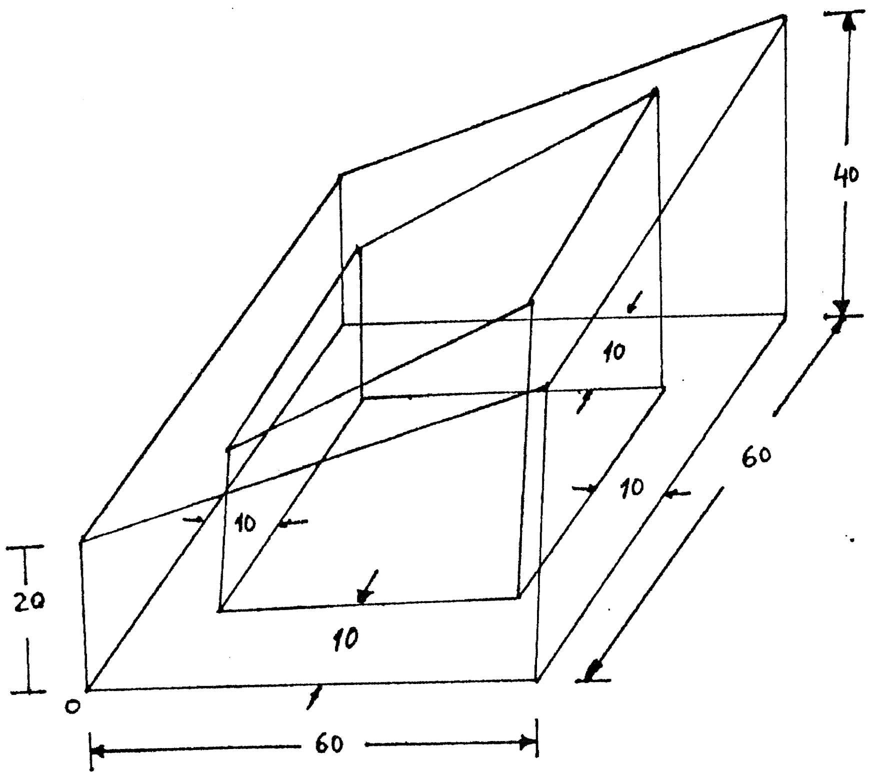


Fig 6.6 Input Part Geometry of Example 3

All dimensions in cms.



SCALE : 1:10



	X	Y	Z
L1 :	58.0	58.0	0.0
L2 :	58.0	2.0	0.0
L3 :	4.0	30.0	0.0
L4 :	0.0	2.0	17.0
L5 :	0.0	58.0	17.0
L6 :	30.0	0.0	17.0
NO C1			
C2 :	60.0	2.0	17.0
C3 :	60.0	58.0	17.0
C4 :	30.0	60.0	17.0

dia of primary locators : 1 cm
dia of Horz. locators : 3.0 cm
(All locators of type rest buttons)

Fig 6.7 Finished Part Geometry of Example 3

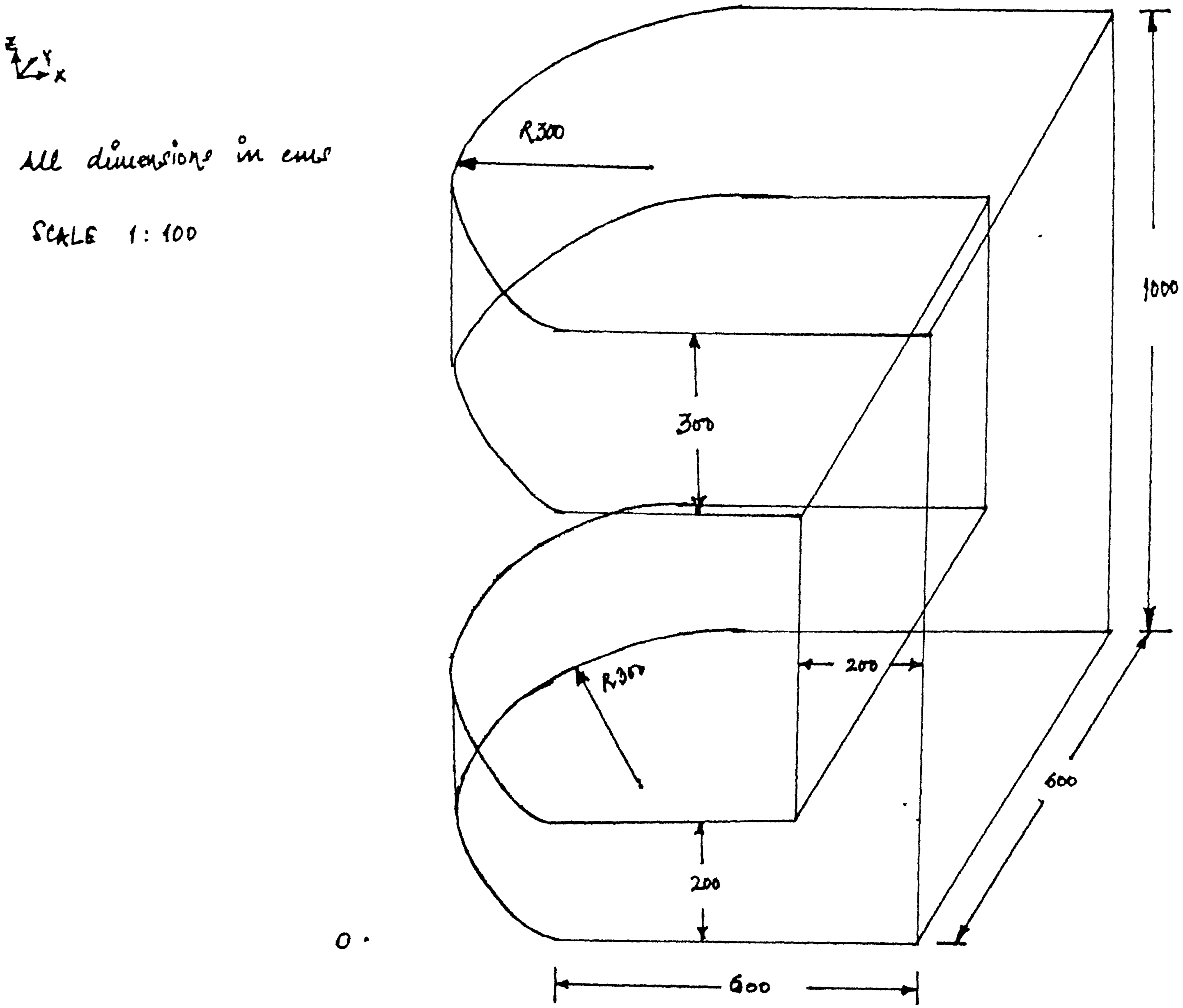
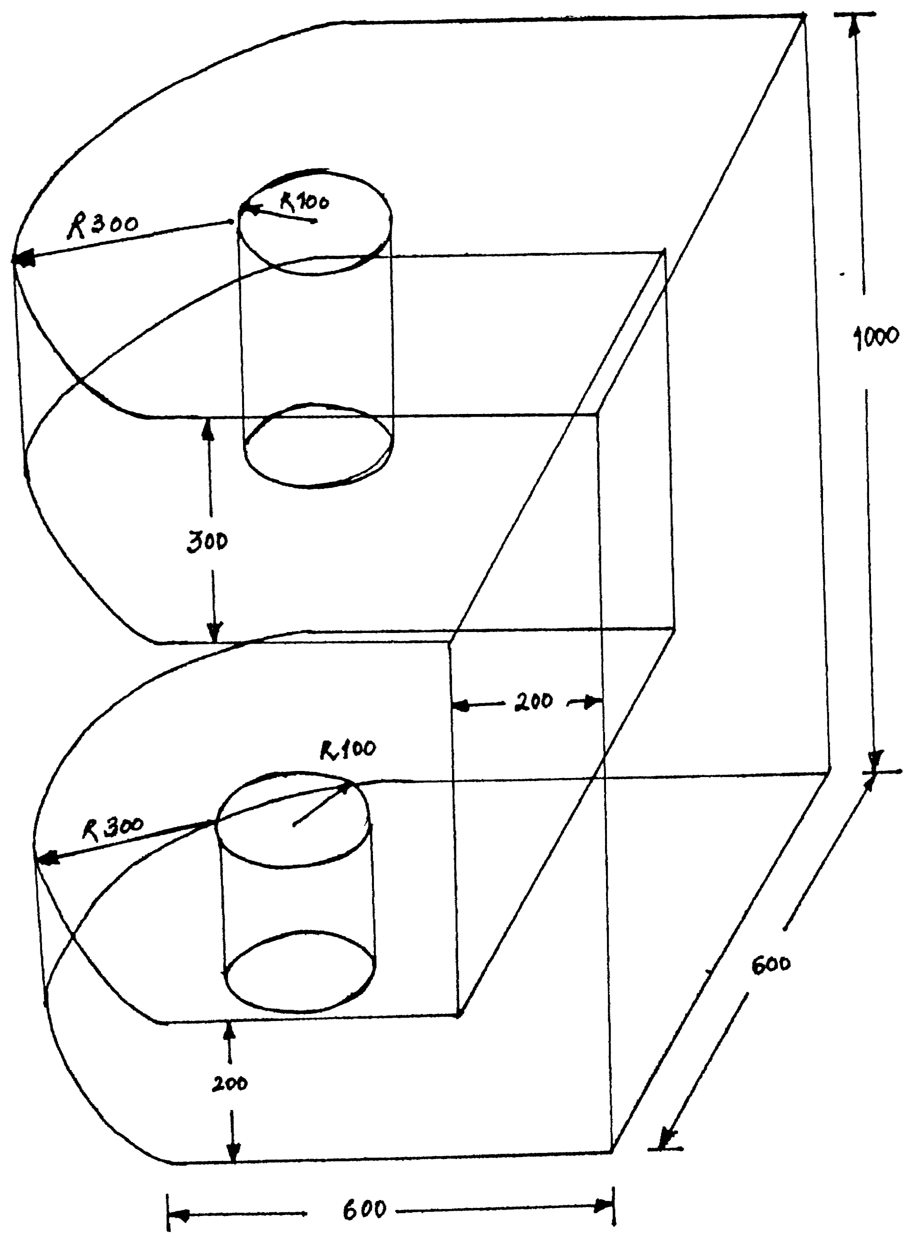


Fig 6.8 Input Part Geometry of Example 4

All dimensions in cms

SCALE : 1:100



	X	Y	Z
L1 :	598.0	598.0	0.0
L2 :	598.0	2.0	0.0
L3 :	4.0	300.0	0.0
L4 :	900.0	2.0	997.0
L5 :	900.0	598.0	997.0
L6 :	450.0	0.0	997.0
C1 :	600.0	300.0	1000.0
C2 :	0.0	2.0	997.0
C3 :	0.0	598.0	997.0
C4 :	450.0	600.0	997.0

Dia of Locators : 40.0 cm

Fig 6.9 Finished Part Geometry of Example 4

CHAPTER 7

CONCLUDING REMARKS AND SCOPE FOR FUTURE WORK

In the present work an effort has been done towards the automation of the machining planning. The primary purpose of the work is to automate the fixture designing module so as to achieve automatic machining planning. Most of the process planning systems perform fixture designing manually, because of intricacies involved in automating it. But for very complex workpiece geometries, this is very tedious and cumbersome task. This problem is also taken care off in the present work due to computational power of modern day computers. The format of the output of the present work is the coordinate of the actual positions of all the possible locators and clamps. This information can be used either for the actual manufacturing of the fixture or with the help of graphics, the fixture can be rendered.

In the present work, most of the difficulties were faced in the field of computational geometry and in converting the knowledge procedures and heuristics into algorithms. The input is taken in the form of faceted boundary representation of a 3D solid model, which is created manually for validation of logic due to the lack of availability of solid modeler. This process is bit time consuming and requires proper attention. But with the availability of solid modeler even this problem will be solved. Another problem, is the non so precise results for curved

objects/surfaces due to the use of faceted boundary representation technique. The procedure also requires special attention for through holes etc.

The results obtained appeared to be quite accurate. As the results are in the form of one good solution with the condition of optimization inserted in the algorithm, hence any comparison among results is not possible.

The estimation of cutting wrenches is not precise but still quite accurate. Thus, with the help of this analysis, elements can be selected and then assembled on the shop floor to obtain modular fixtures, capable of accurately locating the workpiece and restraining its movement by limiting all the twelve degrees of freedom. When raw/blank workpiece is fixtured on such workpiece it will provide accurate final workpiece well within the limits.

There is still a lot which has to be done to achieve a robust automatic machining planning system. Set up planning is not touched in this work and efforts must be done to plan setup planning alongwith fixture designing. It is advisable to do both of these simultaneously.

The combination of feature based model and solid model is a very powerful representation technique for the finished part and the intermediate workpiece in machining planning. The method must be evolved to generate cutter-swept volumes with the help of part geometry and a set of machining features.

A great in depth study is also required to find out the deformation of the workpiece under cutting wrenches and the

clamping forces. 3D Finite Element Analysis (FEA) can be a good tool to achieve it. Then efforts should be undertaken to find maximum allowable deformation for each type of tolerance.

A better method, is also needed to be evolved, for fixturing of a part to be machined from cast or forged raw material.

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